Star formation relations CO SLEDs across the J-ladder and redshift

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UCL

DeMoGas is:

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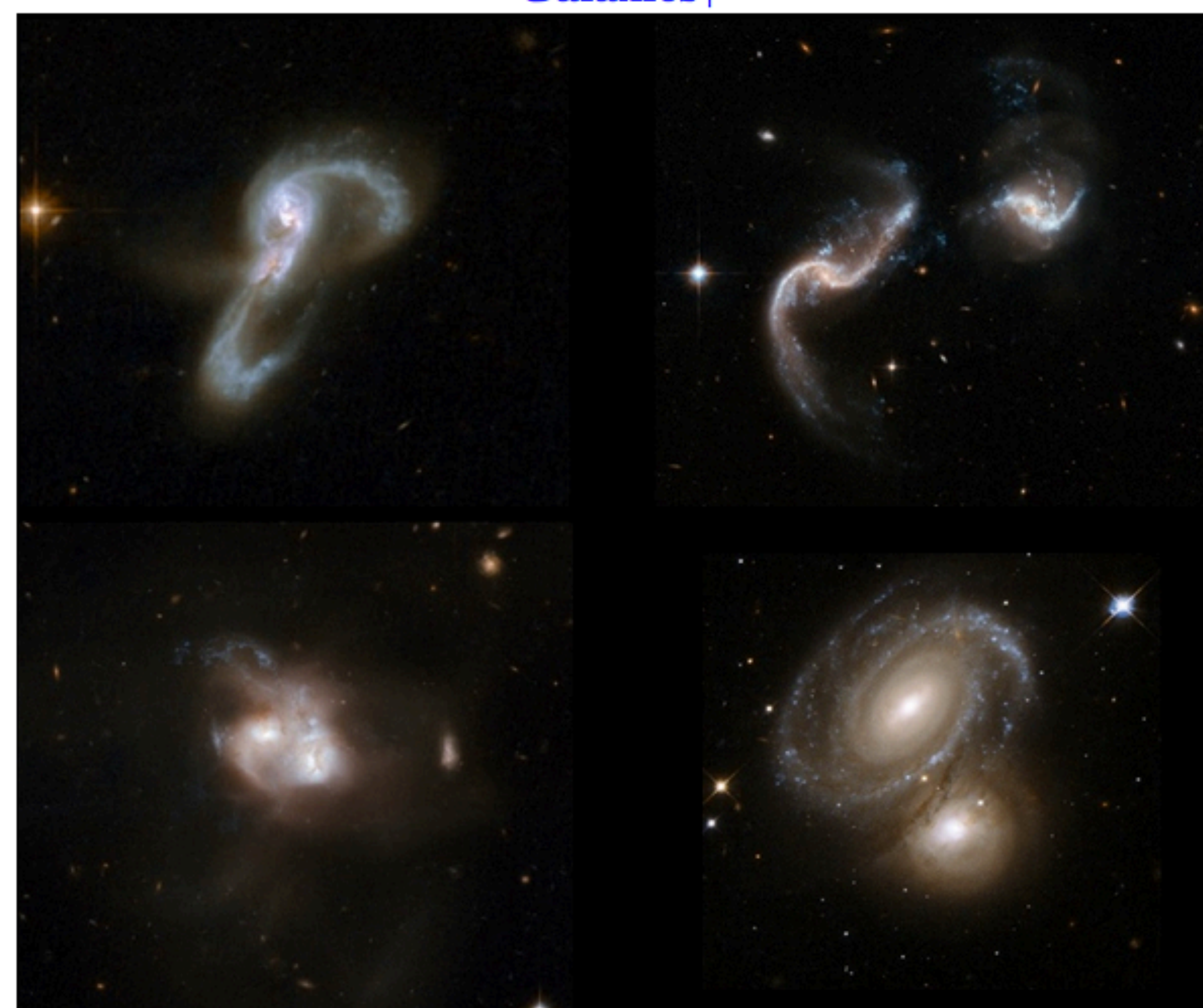
http://demogas.astro.noa.gr/

Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

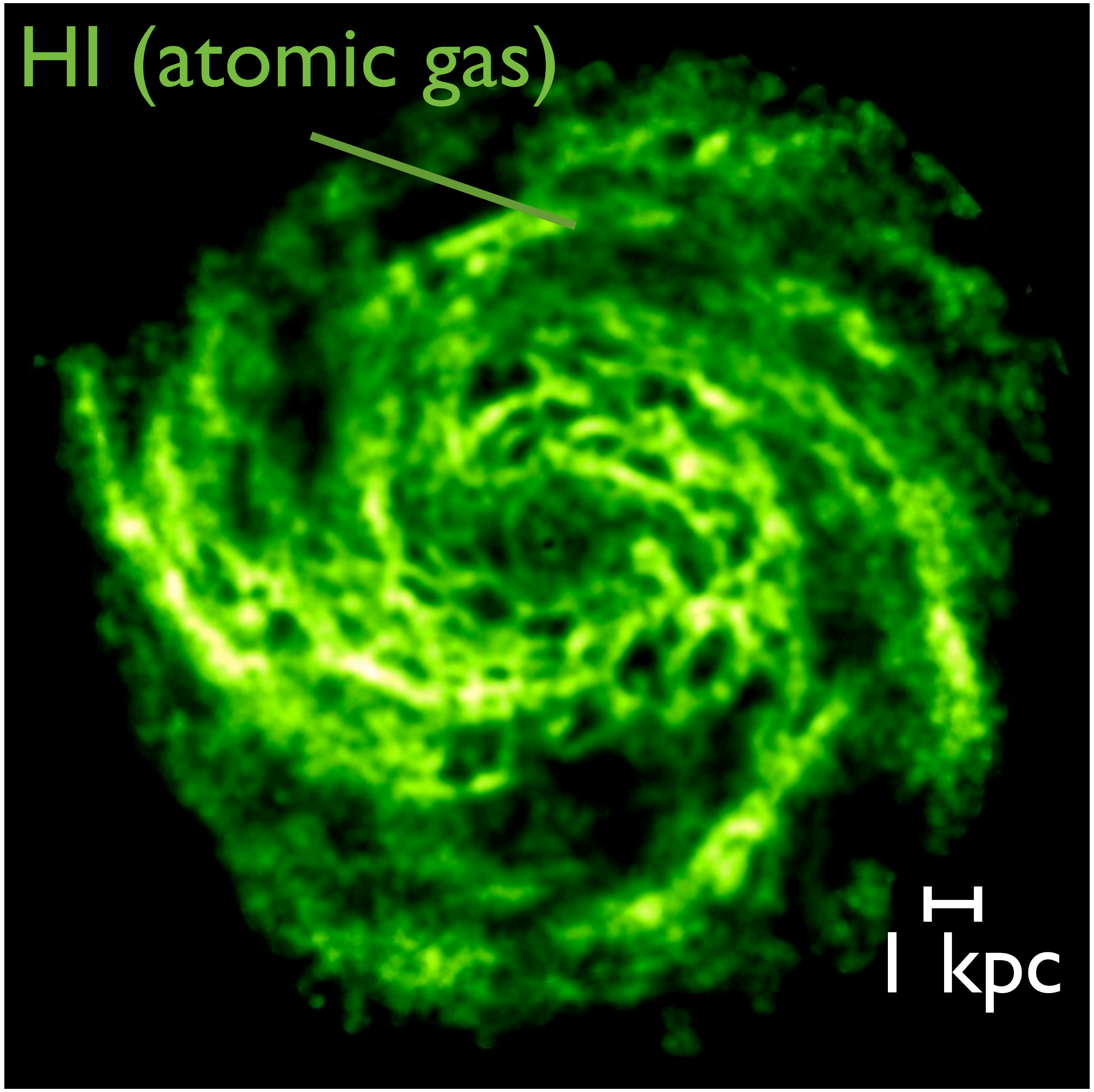
A Step in the Dark: The Dense Molecular Gas (DeMoGas) in Galaxies†



Nottingham February 2014

Why are star formation relations interesting?

IC342

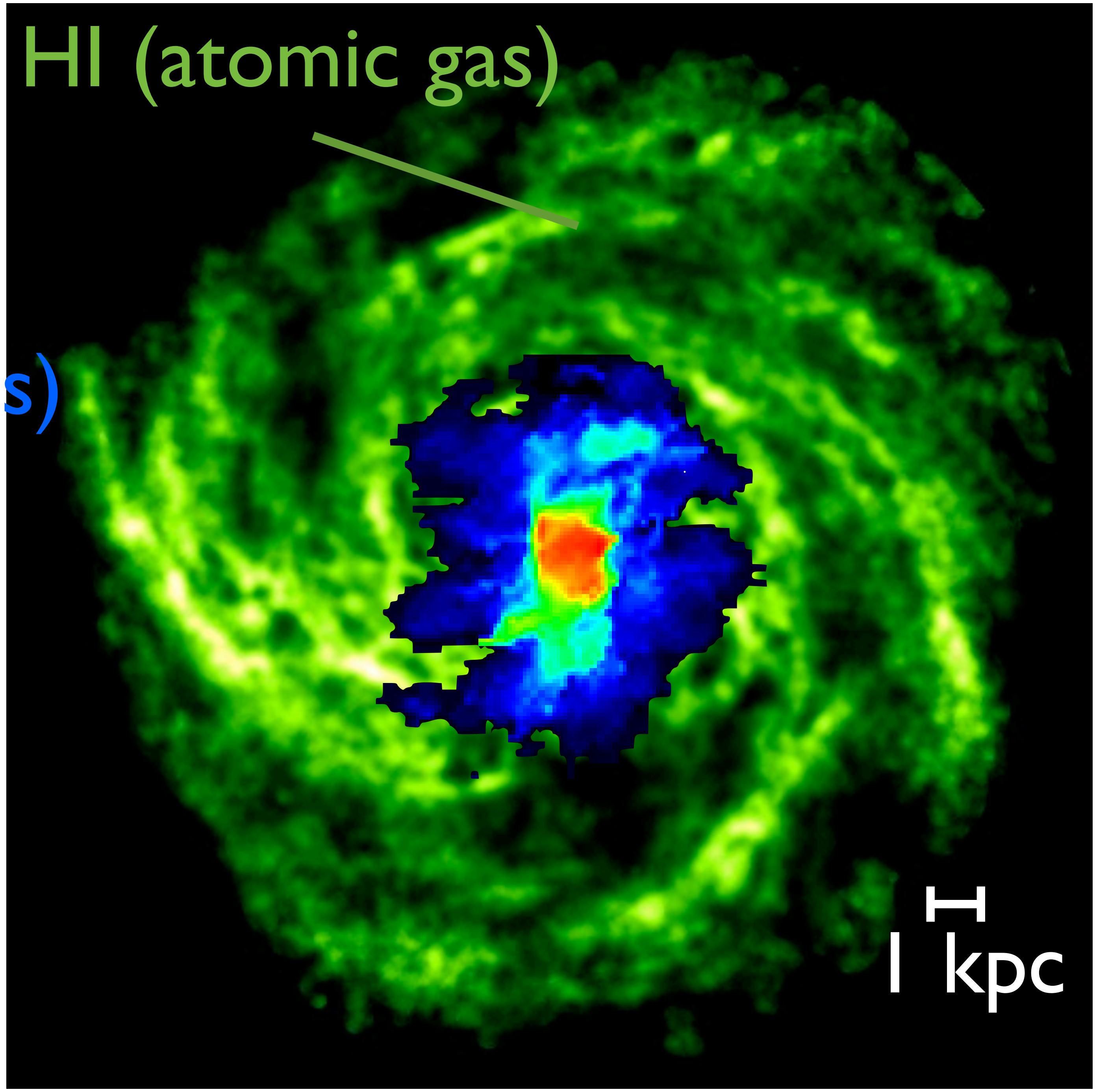


THINGS

Why are star formation relations interesting?

IC342

^{12}CO J=1-0 (molecular gas)



THINGS

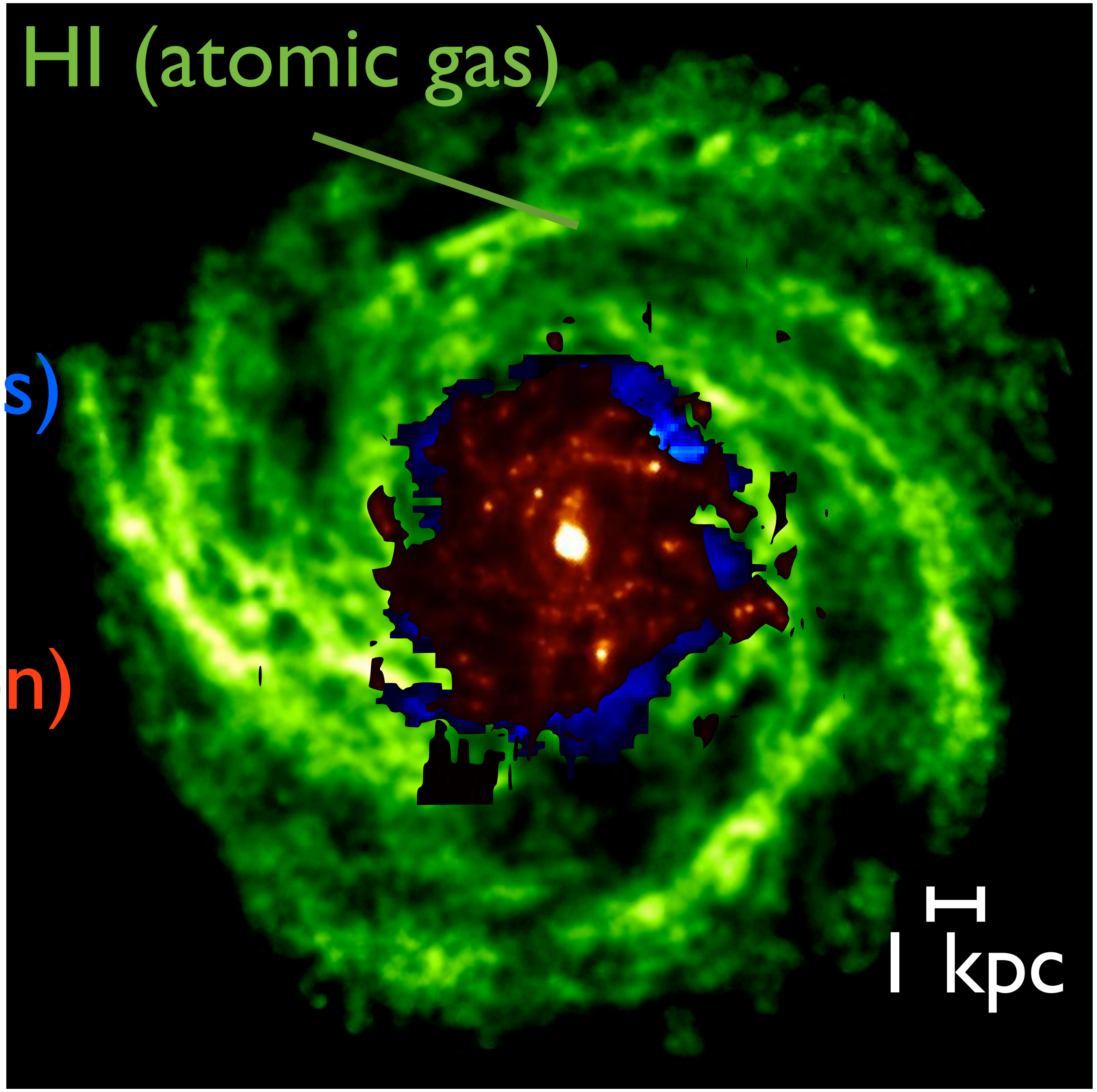
NRAO 12m

Why are star formation relations interesting?

IC342

^{12}CO J=1-0 (molecular gas)

IR emission (star formation)



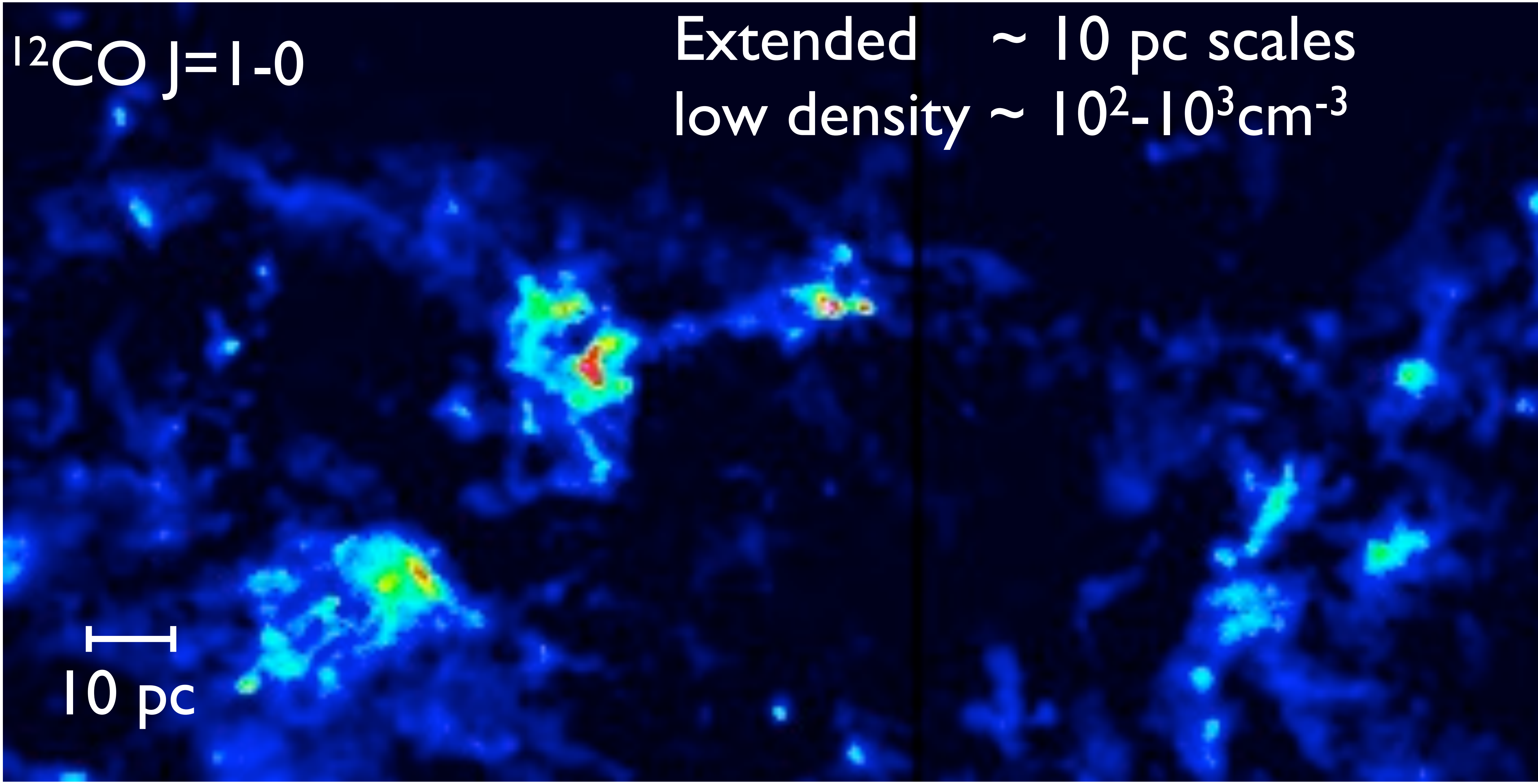
THINGS

NRAO 12m

Spitzer 70um

On kpc scales, SFR is related to H_2 gas rather than HI

Star formation relations in our Galaxy



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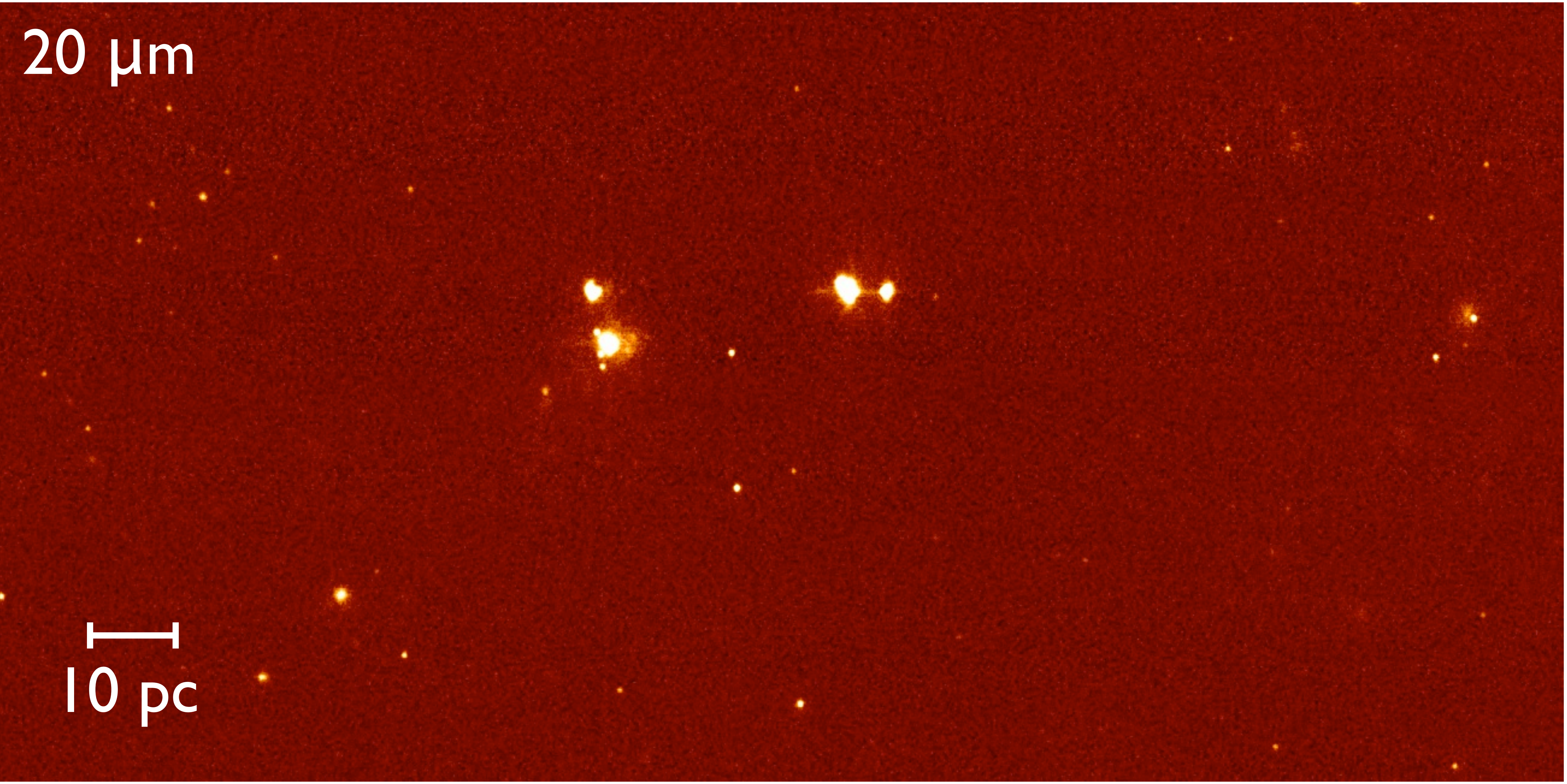

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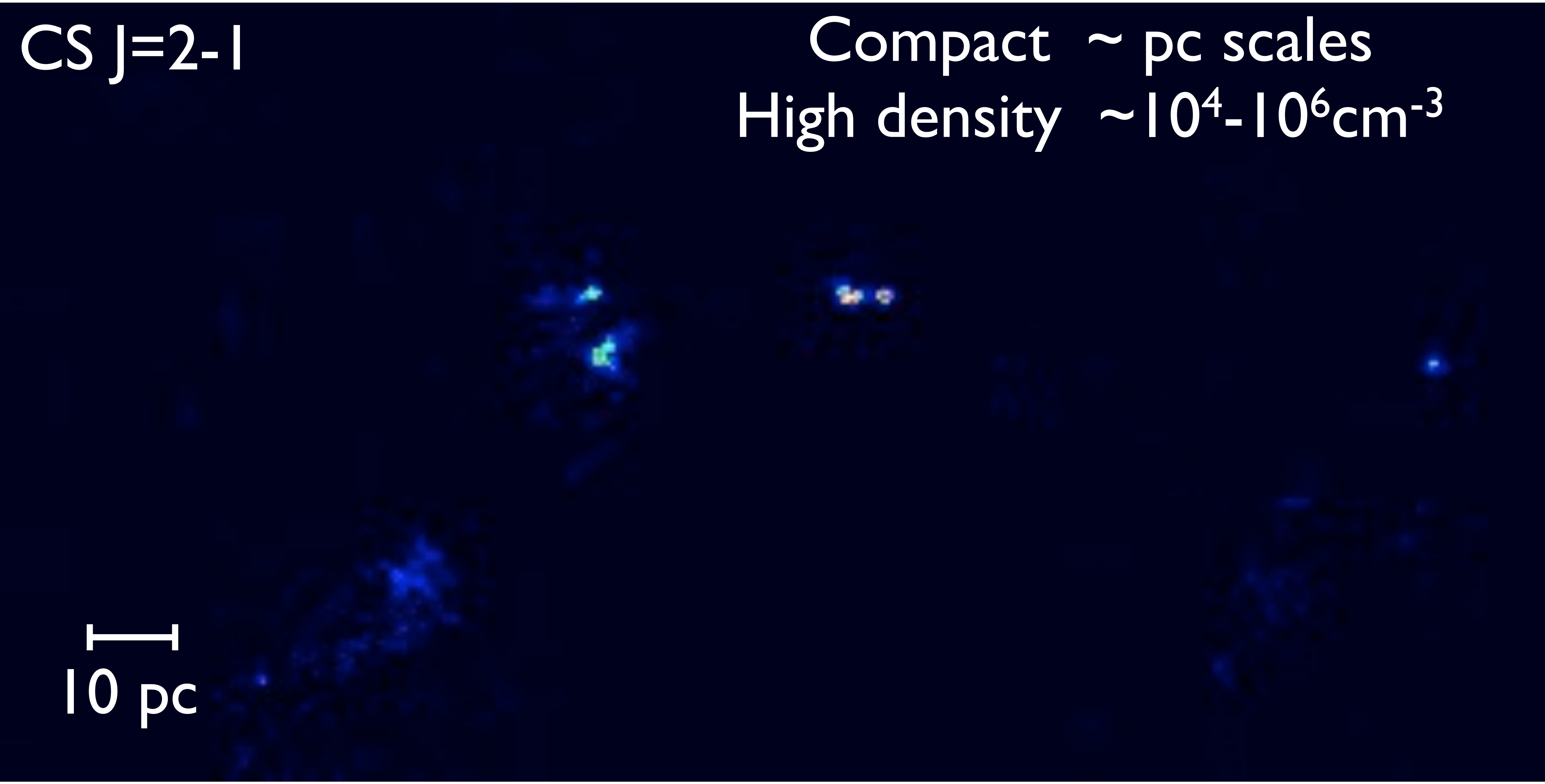
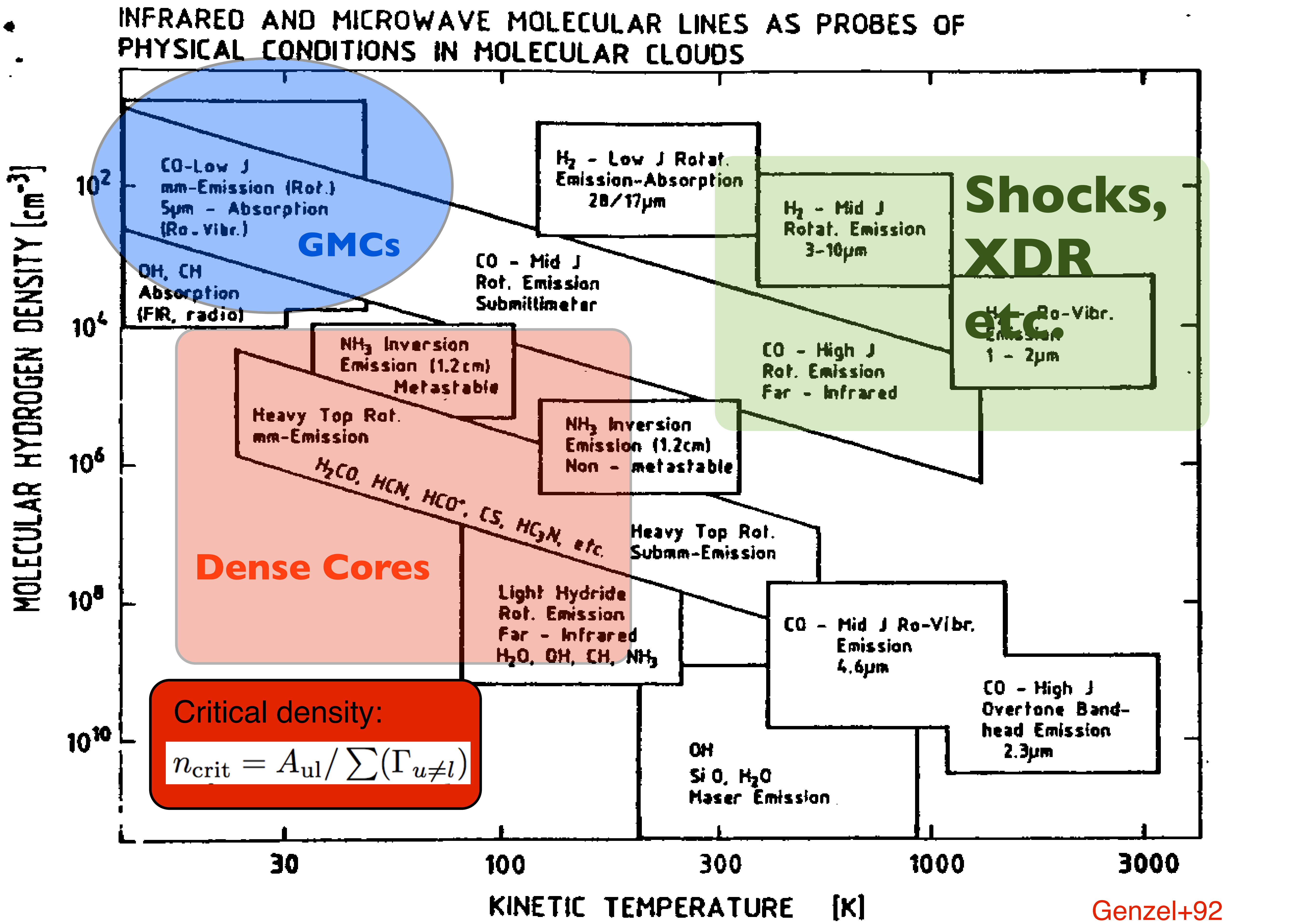




INFRARED AND MICROWAVE MOLECULAR LINES AS PROBES OF PHYSICAL CONDITIONS IN MOLECULAR CLOUDS
MOLECULAR HYDROGEN DENSITY [cm^{-3}]
10^2
10^4
10^6
10^8
10^{10}
KINETIC TEMPERATURE [K]
30
100
300
1000
3000
CO-Low J mm-Emission (Rot.) 5μm - Absorption (Ro.-Vibr.)
OH, CH Absorption (FIR, radio)
GMCs
H_2 - Low J Rotat. Emission-Absorption 28/17μm
CO - Mid J Rot. Emission Submillimeter
H_2 - Mid J Rotat. Emission 3-10μm
Shocks, XDR etc.
H_2 - Ro-Vibr. Emission 1 - 2μm
CO - High J Rot. Emission Far - Infrared
NH_3 Inversion Emission (1.2cm) Metastable
Heavy Top Rot. mm-Emission
NH_3 Inversion Emission (1.2cm) Non - metastable
H_2CO, HCN, HCO^+, CS, HC_3N, etc.
Heavy Top Rot. Submm-Emission
Dense Cores
Light Hydride Rot. Emission Far - Infrared H_2O, OH, CH, NH_3
CO - Mid J Ro-Vibr. Emission 4.6μm
CO - High J Overtone Band-head Emission 2.3μm
OH SiO, H_2O Maser Emission
Critical density:
$n_{\rm crit} = A_{\rm ul}/\sum(\Gamma_{u\neq l})$
Genzel+92

Star formation 'laws'

'The Schmidt-Kennicutt law'

Schmidt (1959):

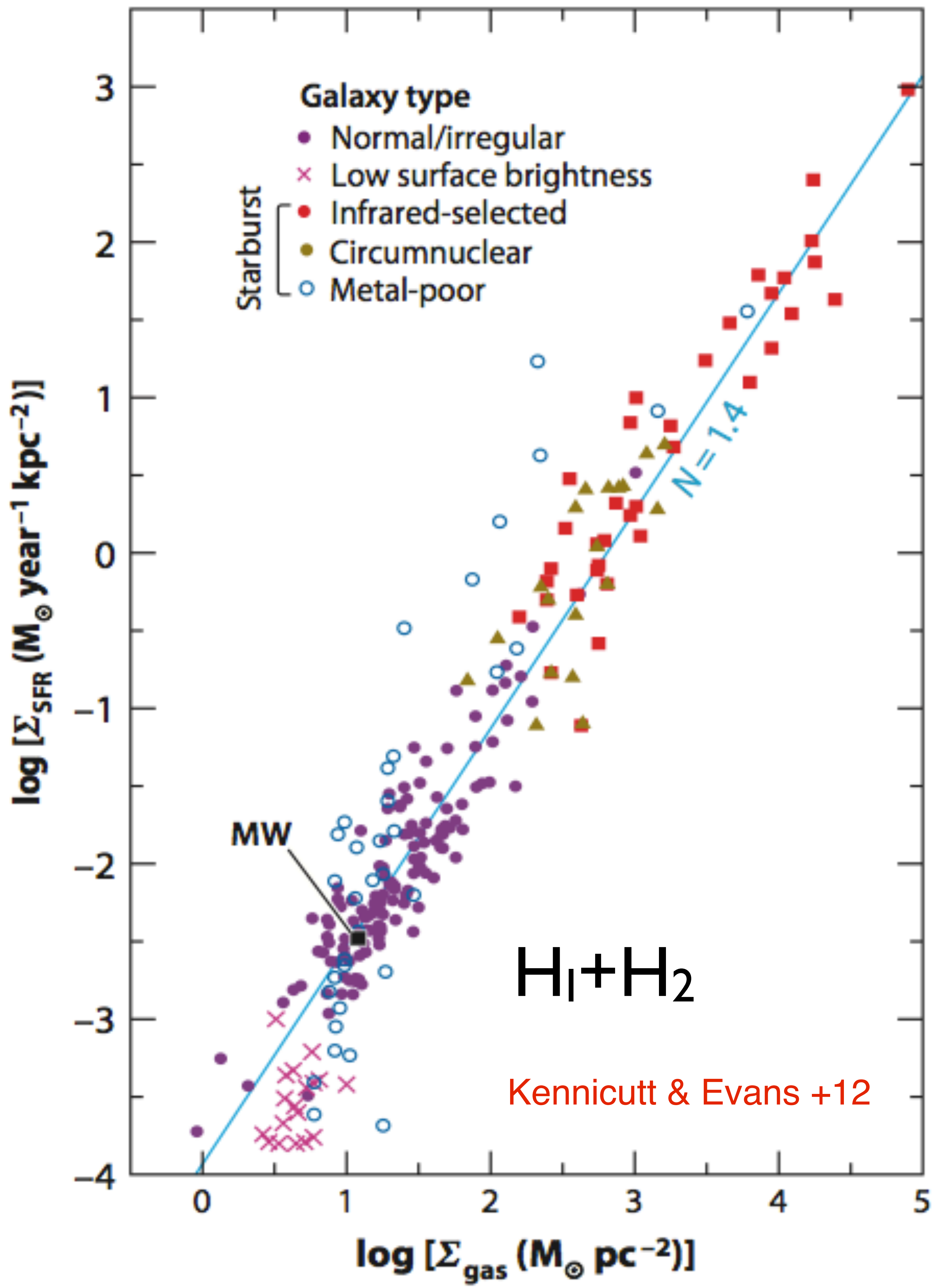
$$\rho_{\mathrm{SFR}} \sim \rho^N \qquad N \sim 2$$

Kennicutt (1998):
(If constant scale height)

$$\Sigma_{\mathrm{SFR}} = A\Sigma_{\mathrm{gas}}^N \qquad N \sim 1.4$$

Issues:

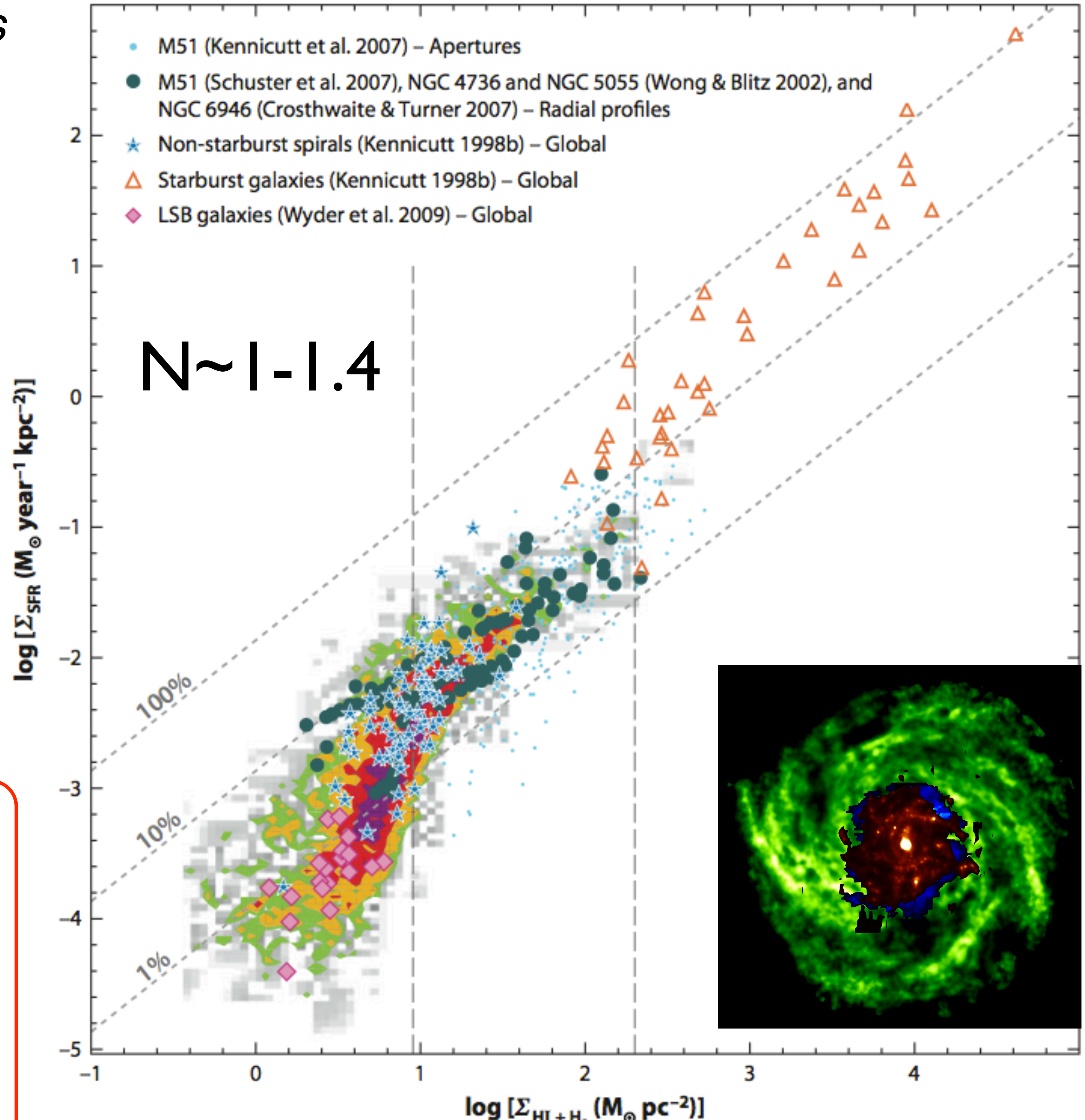
- X(CO)
- Metallicity
- $H_2/(H_2+HI)$ fraction
- ...



Star formation 'laws'

Resolved on sub-kpc scales

SINGS, THINGS, KINGFISH surveys...



Kennicutt & Evans +12

<u>100pc-1kpc scales:</u>

- SFR-H_2 correlation

<u>< 50-100pc scales:</u>

- 'break-down' due to undersampling

<u>H_2-HI transition:</u>

- ~10$M_\odot$ pc^{-2}
- No SFR-HI correlation

<u>Issues:</u>

- X(CO)
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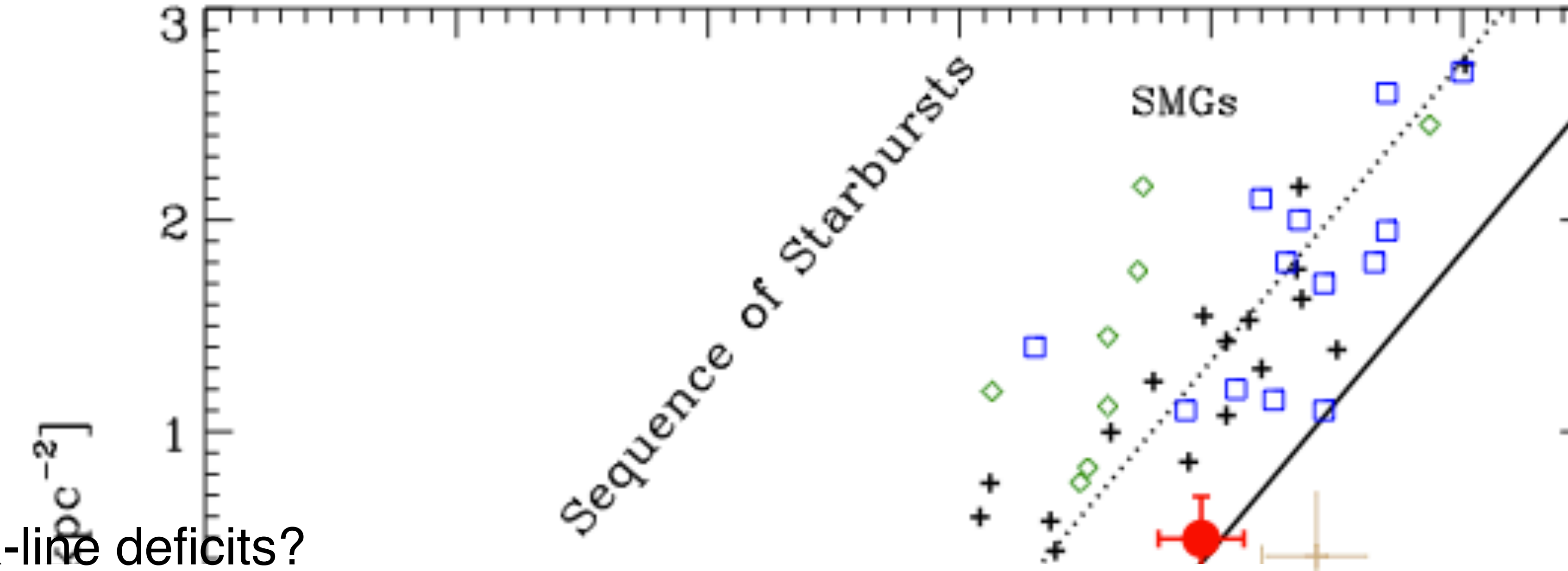
- H_2/(H_2+HI) fraction
- ...

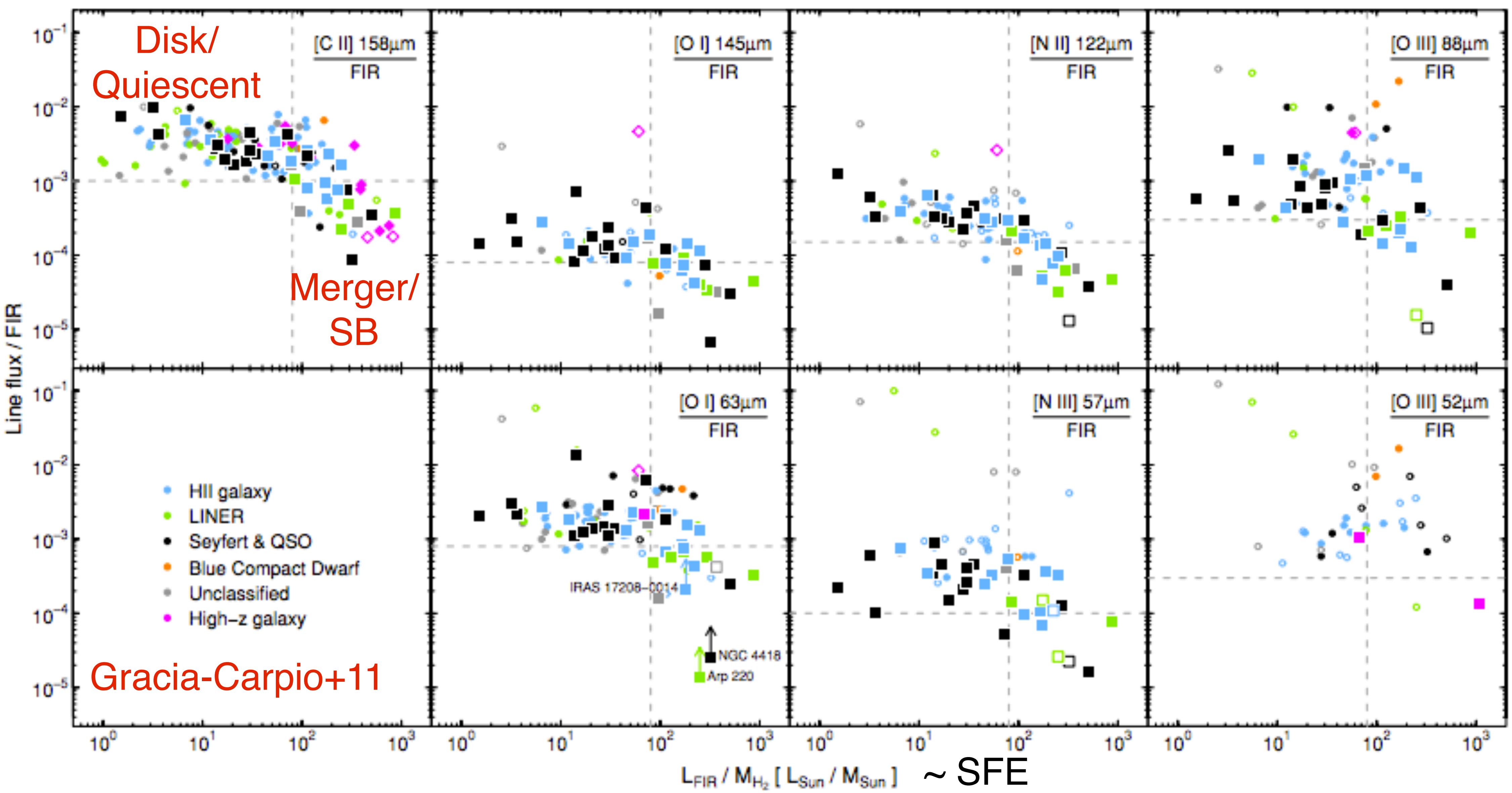
Star formation ‘laws’

Bi-modal SF laws?

- Starburst mergers vs. quiescent disks
- Enhanced SFE in mergers
- Compact vs. extended gas configuratior
- ISM energy density (UV, CR, turb.)



Evidence for bi-modal SF in FIR-line deficits?



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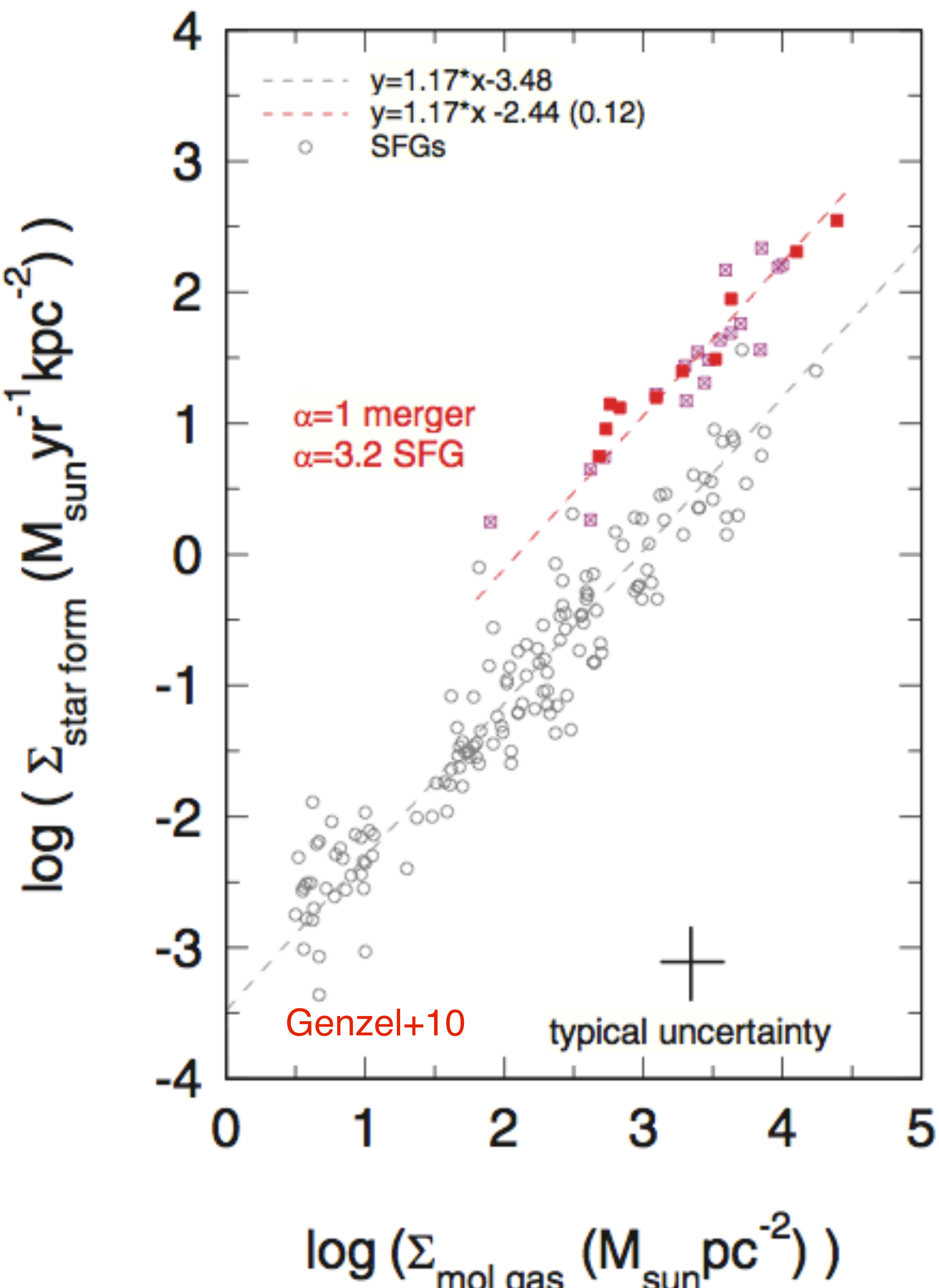
Issues:

- Two separate X(CO) used!
- Heterogenous samples
- Poorly sampled SEDs / L_{IR} uncertain
- Sizes are uncertain at high-z
- AGN contamination harder to assess
- Mixing J-transitions



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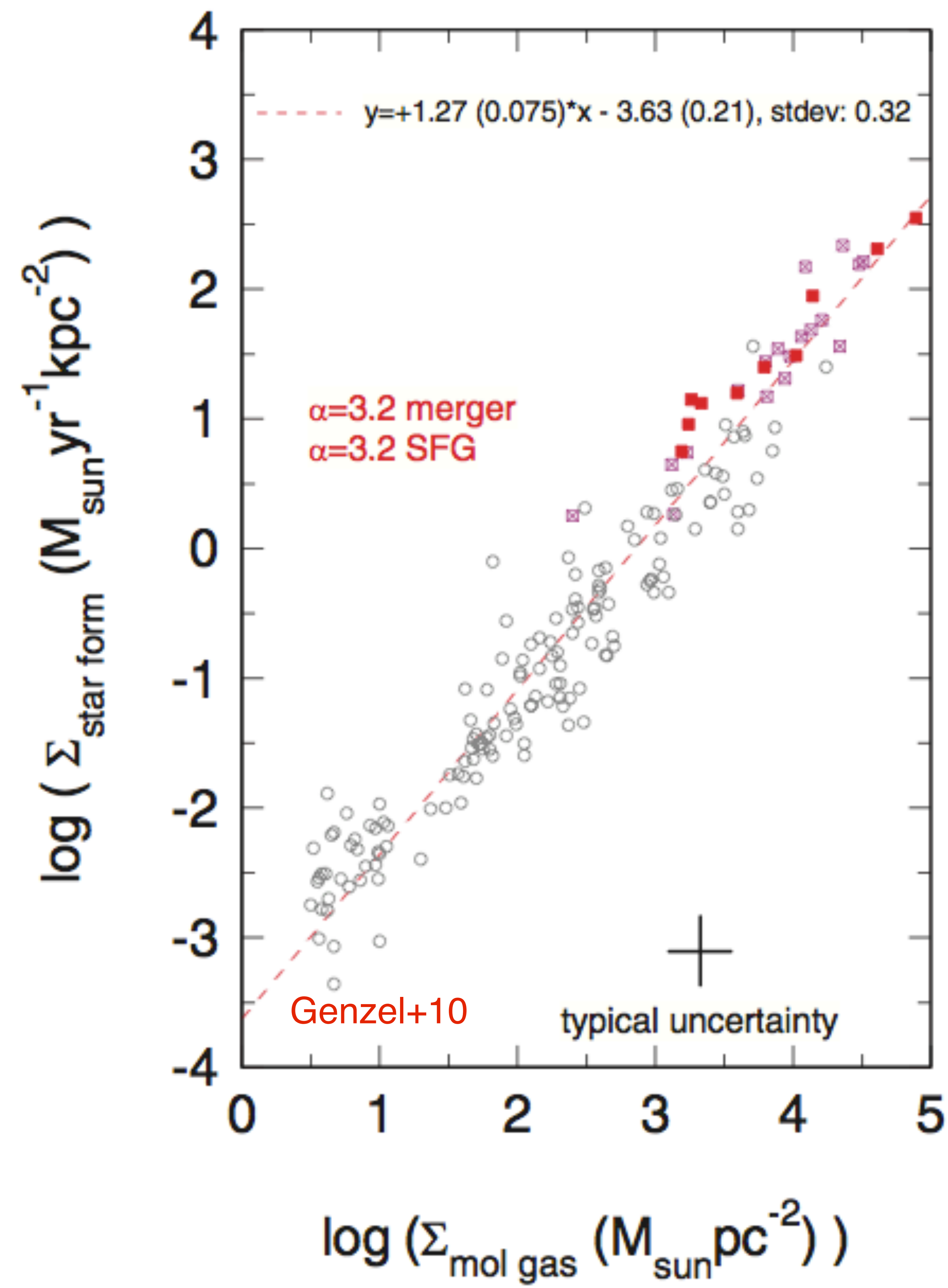

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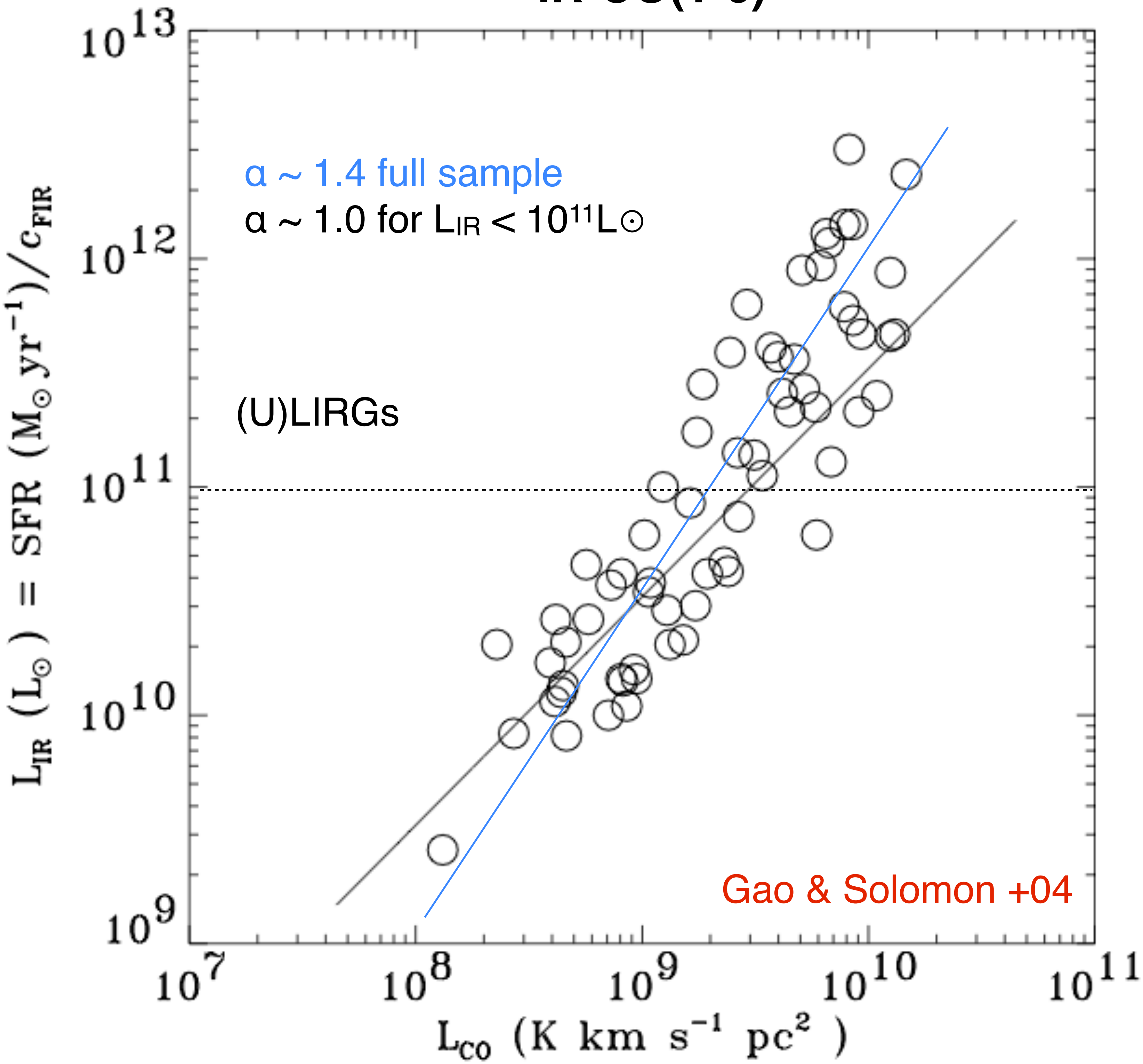
Luminosity (IR-dense gas) relations of local galaxies

Proxy-relations

IR-CO(1-0)



Important side-note:

Kennicutt-Schmidt law:

$$\Sigma_{\rm SFR} = A\Sigma^N_{\rm gas}$$

Proxy: luminosity relation

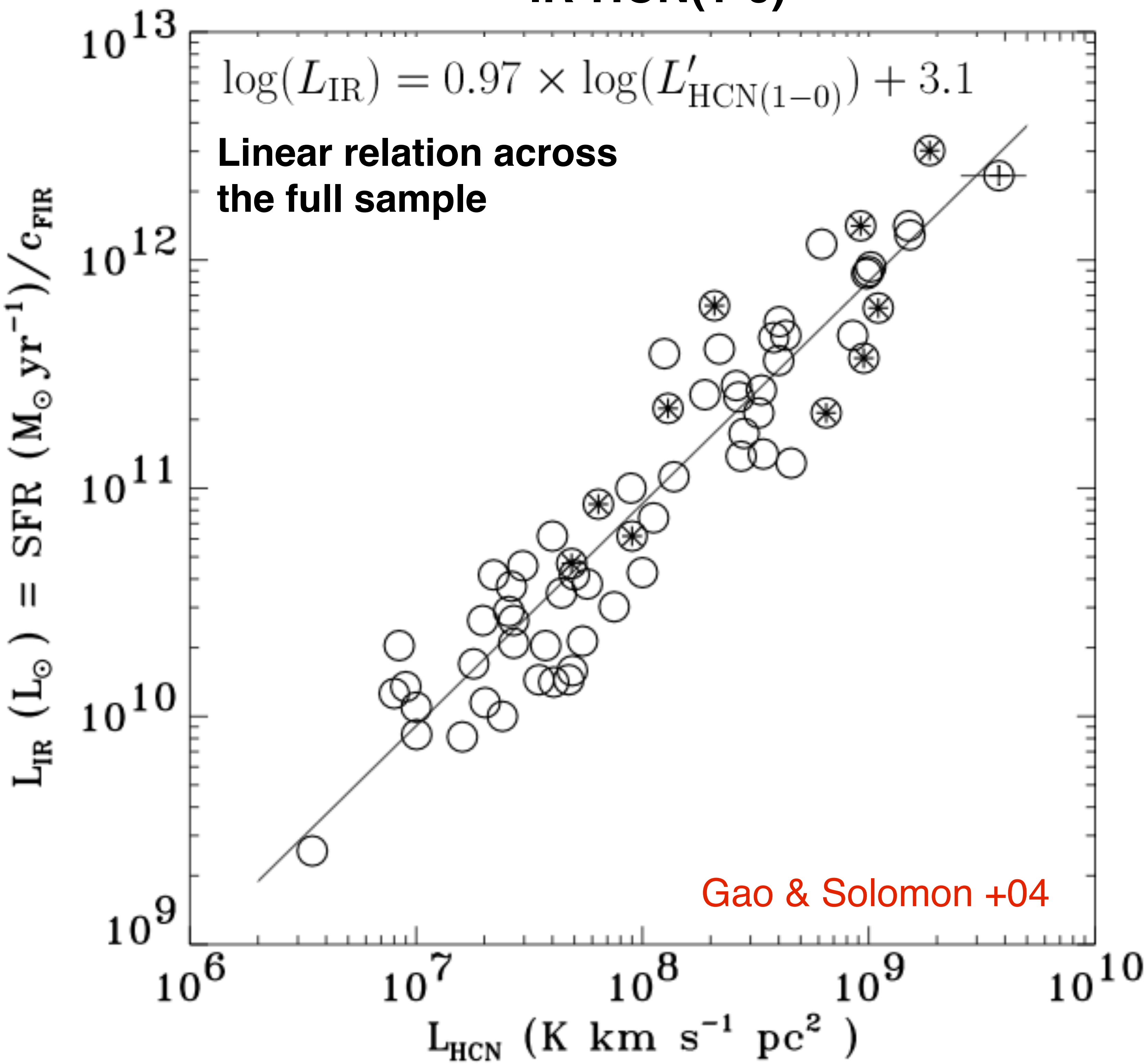
$$\log L_{\rm IR} = \alpha \log L_{\rm mol} + \beta$$

- Size measurements difficult: few interferometric or single-dish on-the-fly CO/HCN/CS maps exist.
- CO (and HCN/CS) conversion to gas mass dubious, and requires extensive modeling.
- Dense gas mass fraction require multi-line observations and multi-phase (LVG) modeling (Greve et al. 2009)

Luminosity (IR-dense gas) relations of local galaxies

Dense gas proxy-relations

IR-HCN(1-0)



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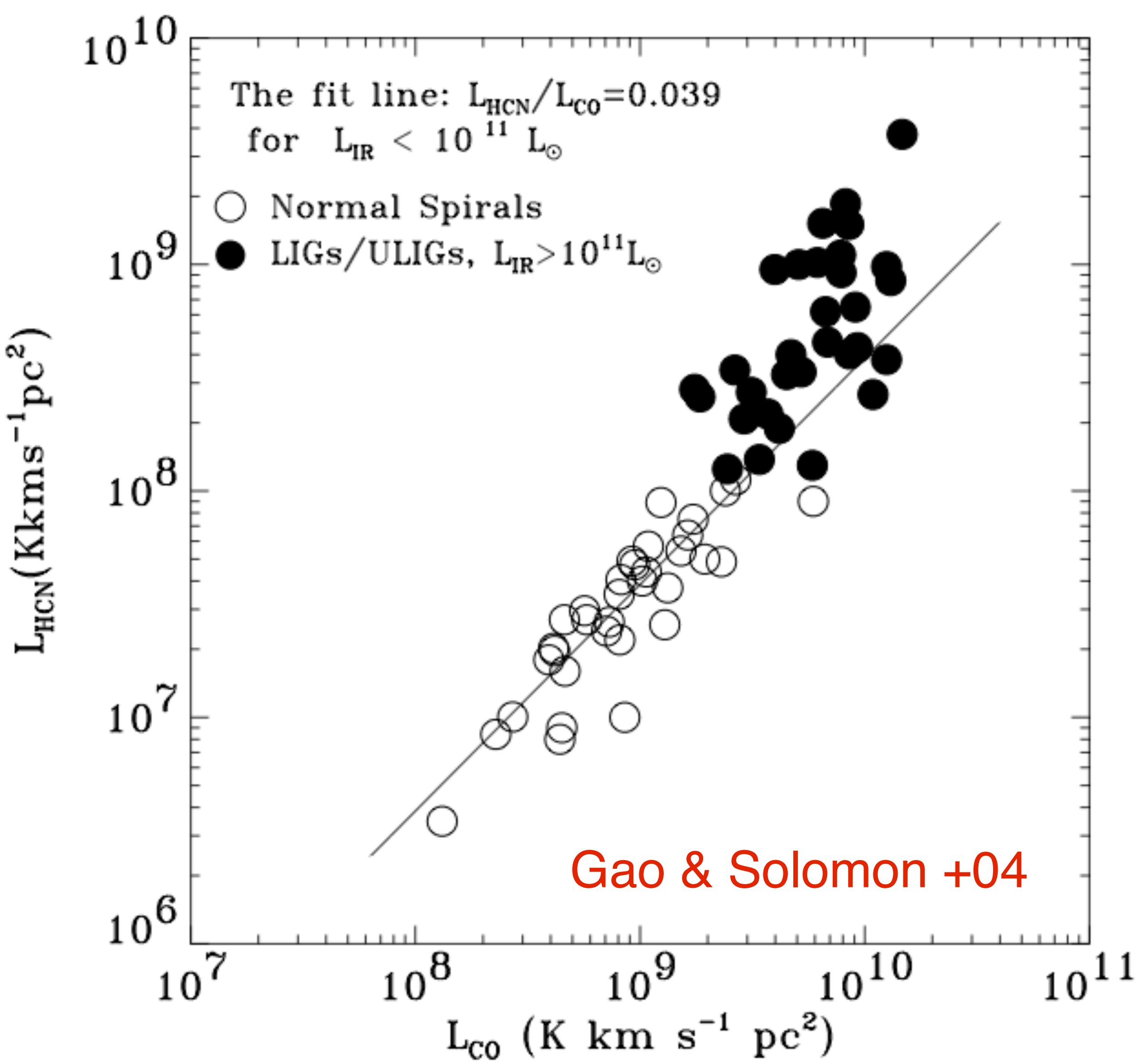
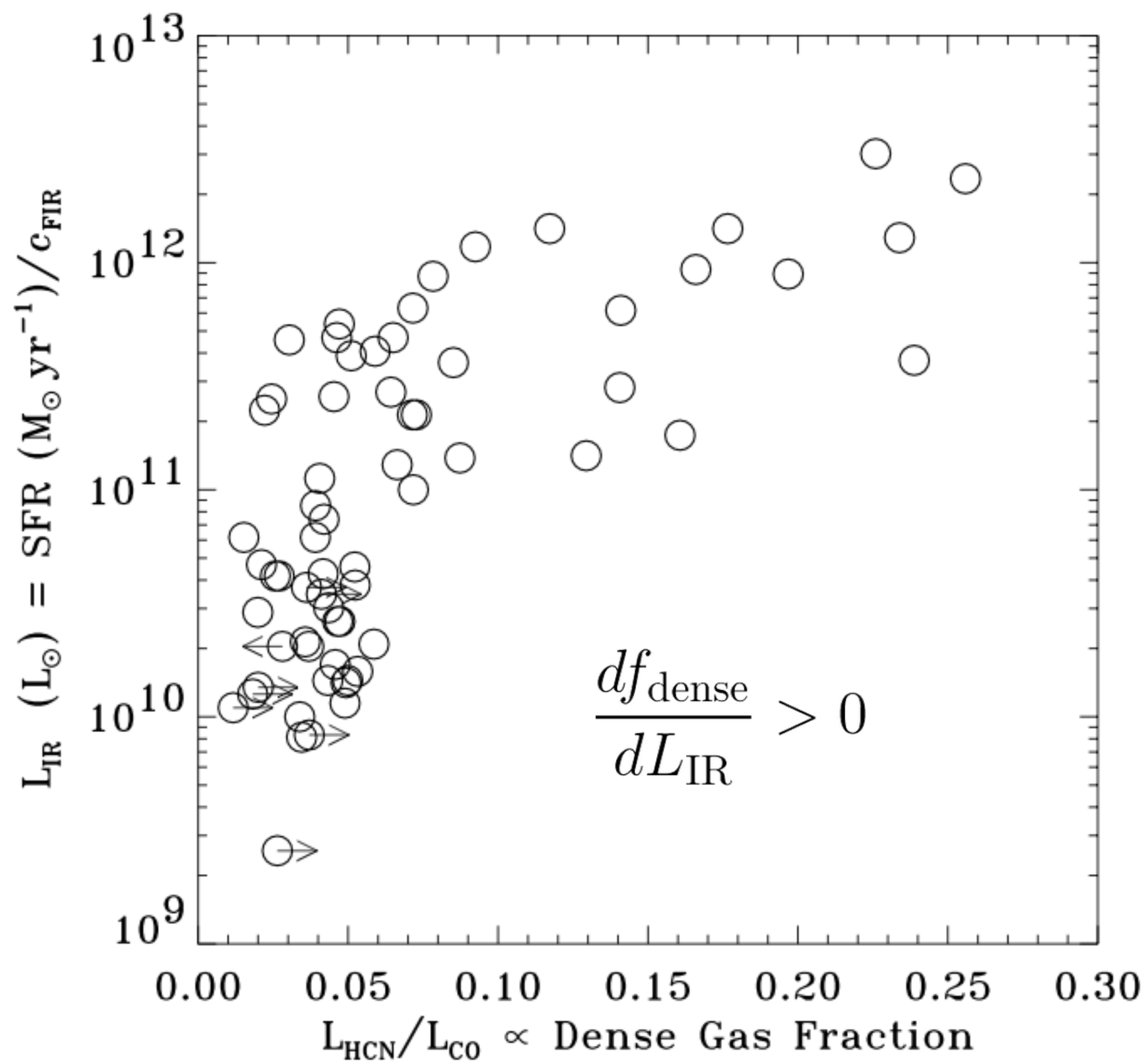
Luminosity (IR-dense gas) relations of local galaxies

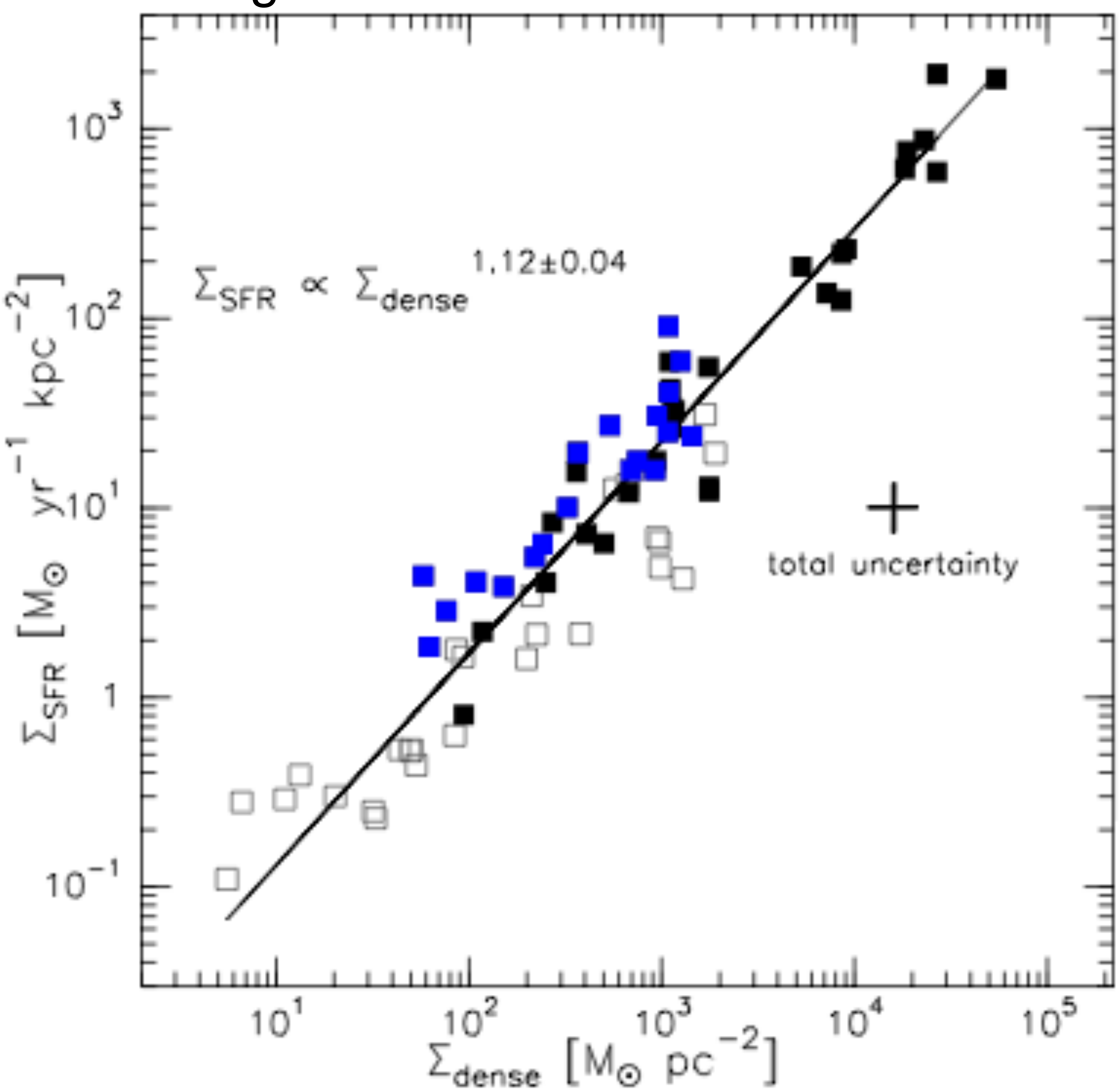
- (U)LIRGs have higher HCN/CO (i.e. dense gas fractions) than normal spirals.
- This explains the super-linear IR-CO relations ('mixing' populations)
- Bimodal IR-CO relations, with f_{dense} setting the IR-CO normalisation (β)



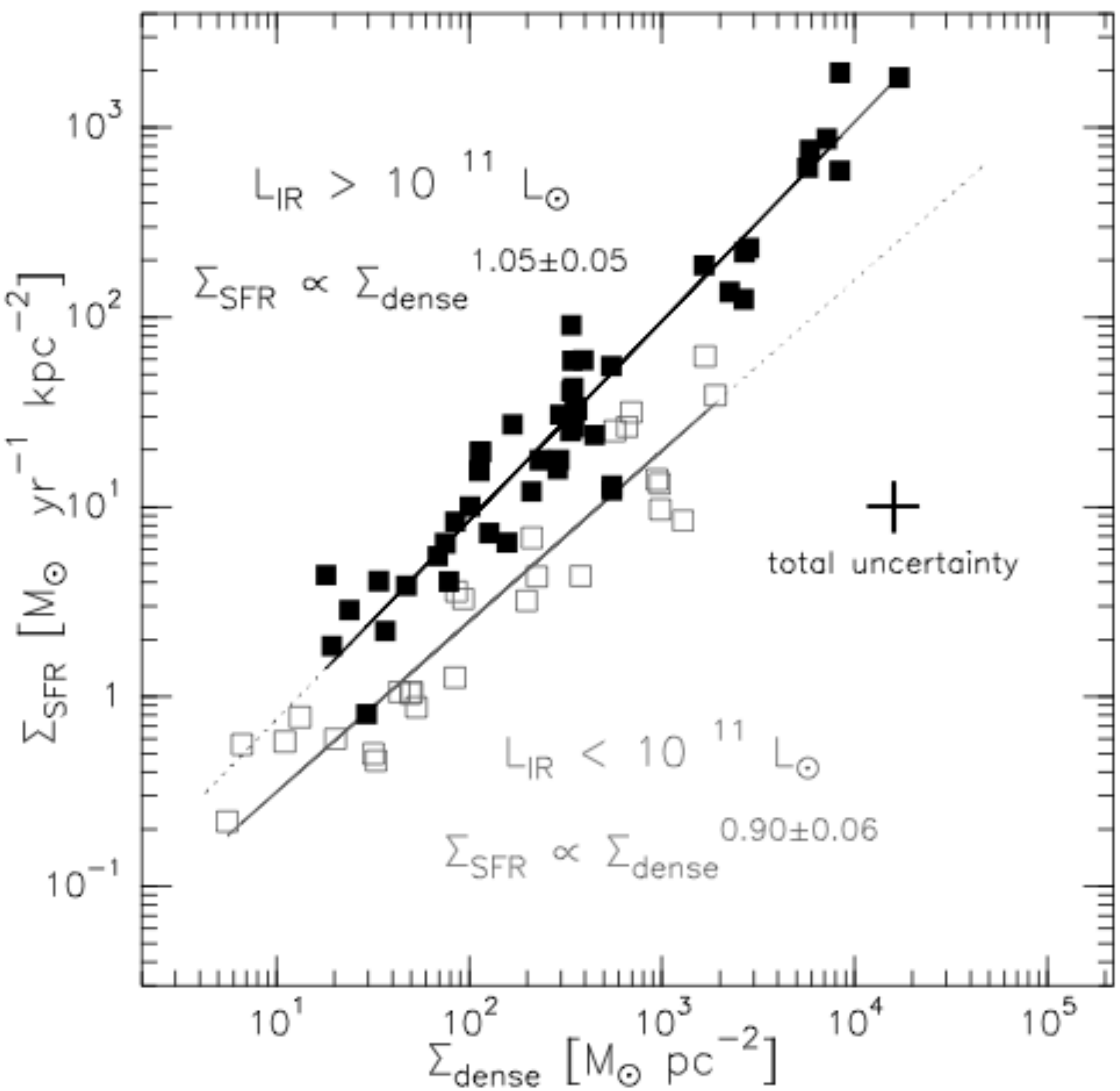


Luminosity (IR-dense gas) relations of local galaxies

A single linear dense SF law?



A bi-modal dense SF laws as for CO?



Gracia-Carpio+12

Star formation 'laws'

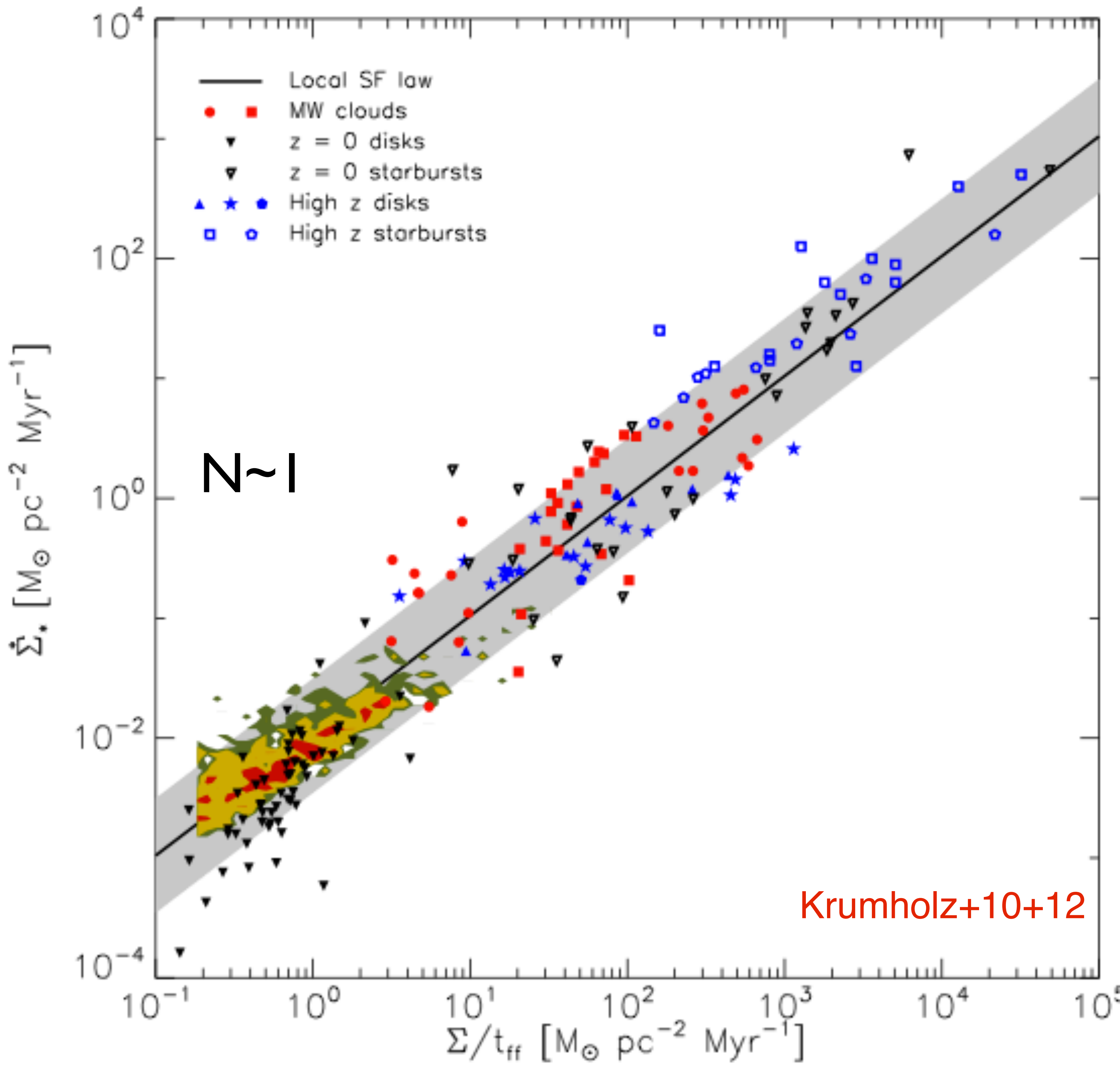
Theory - a universal SF law?

$$t_{\rm ff} \propto \rho^{-1/2}$$

$$SFR \sim \frac{M_{\rm gas}}{t_{\rm ff}} \propto \rho^{1.5}$$

$$\Sigma_{\rm SFR} = \overbrace{f_{\rm H_2}\epsilon_{\rm ff}}^{\sim 1\%}\frac{\Sigma_{\rm gas}}{t_{\rm ff}}$$

- SF laws are set by **local** conditions/ time-scales (not global, e.g. t_{dyn}, t_{orb})
- Only gravity (plus SF efficiency)
- Explains observed slopes
- Different scale heights (h) removes bi-modality
- ...but observational determinations of h are highly uncertain

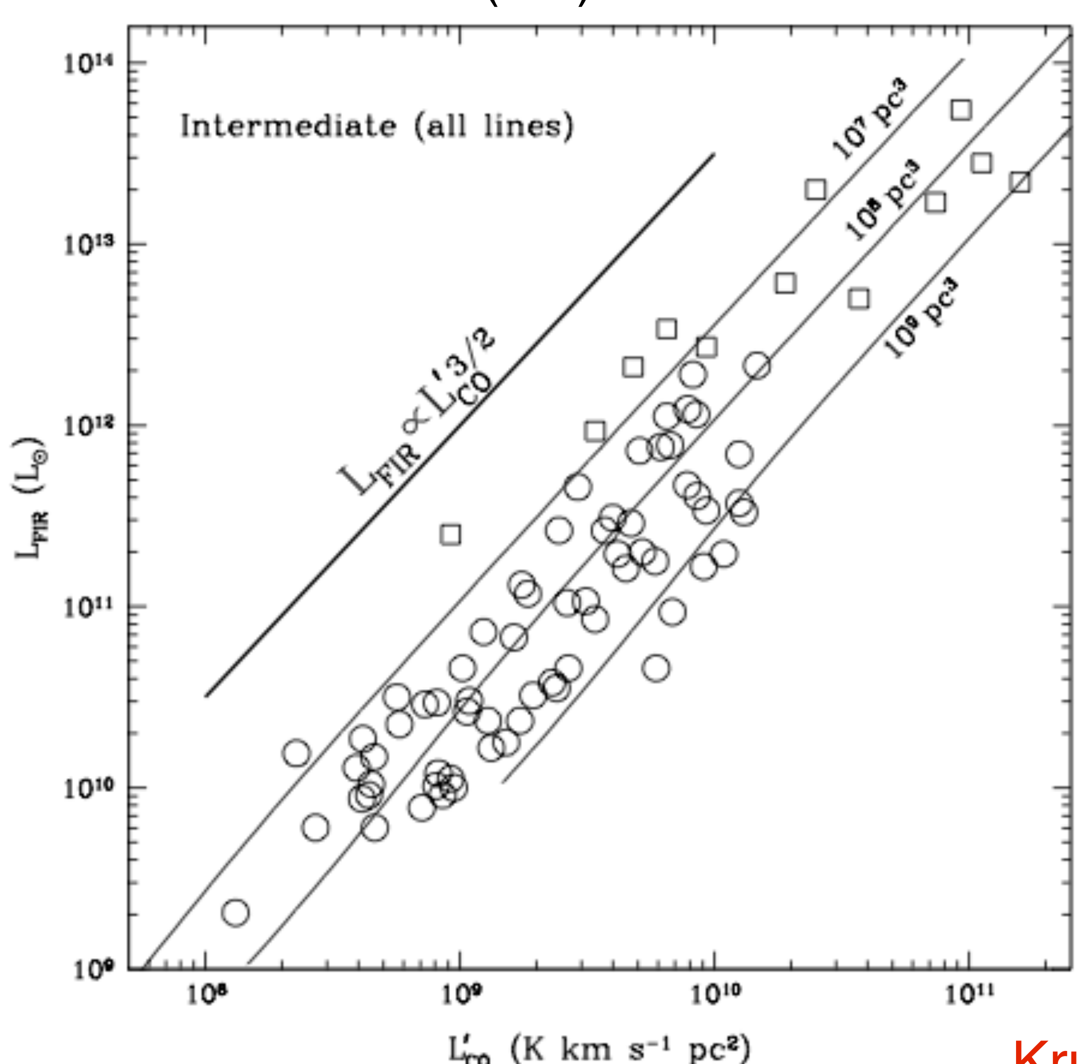


Predictions by the only two models on the market

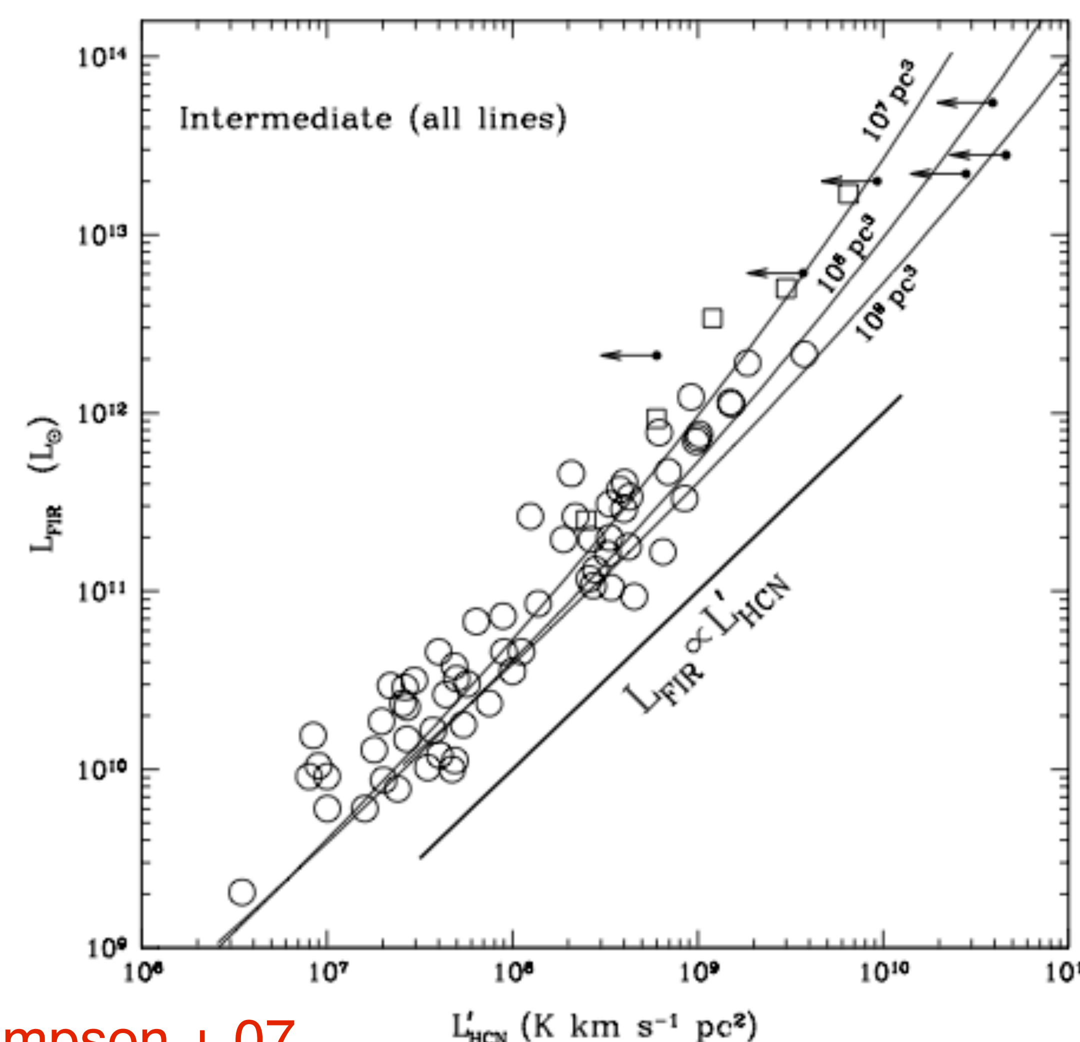
Krumholz & McKee+05; Krumholz & Thompson+07; Narayanan+08

- Both assume an underlying Kennicutt-Schmidt law: $\rho_{\rm SFR} \propto \rho_{\rm gas}^{1.5}$
- Highly turbulent (*Mach number*) ISM, where SF occurs in virialized, (near-)isothermal gas clouds at low temps. (T_k~10-30K)
- thus valid L_{IR}-L'_{mol} predictions over a large density range, but only applicable for lines with $E_J/k_B < 30K$, i.e low-J lines of CO and heavy rotor molecules

CO(1-0)



HCN(1-0)



Krumholz & Thompson + 07

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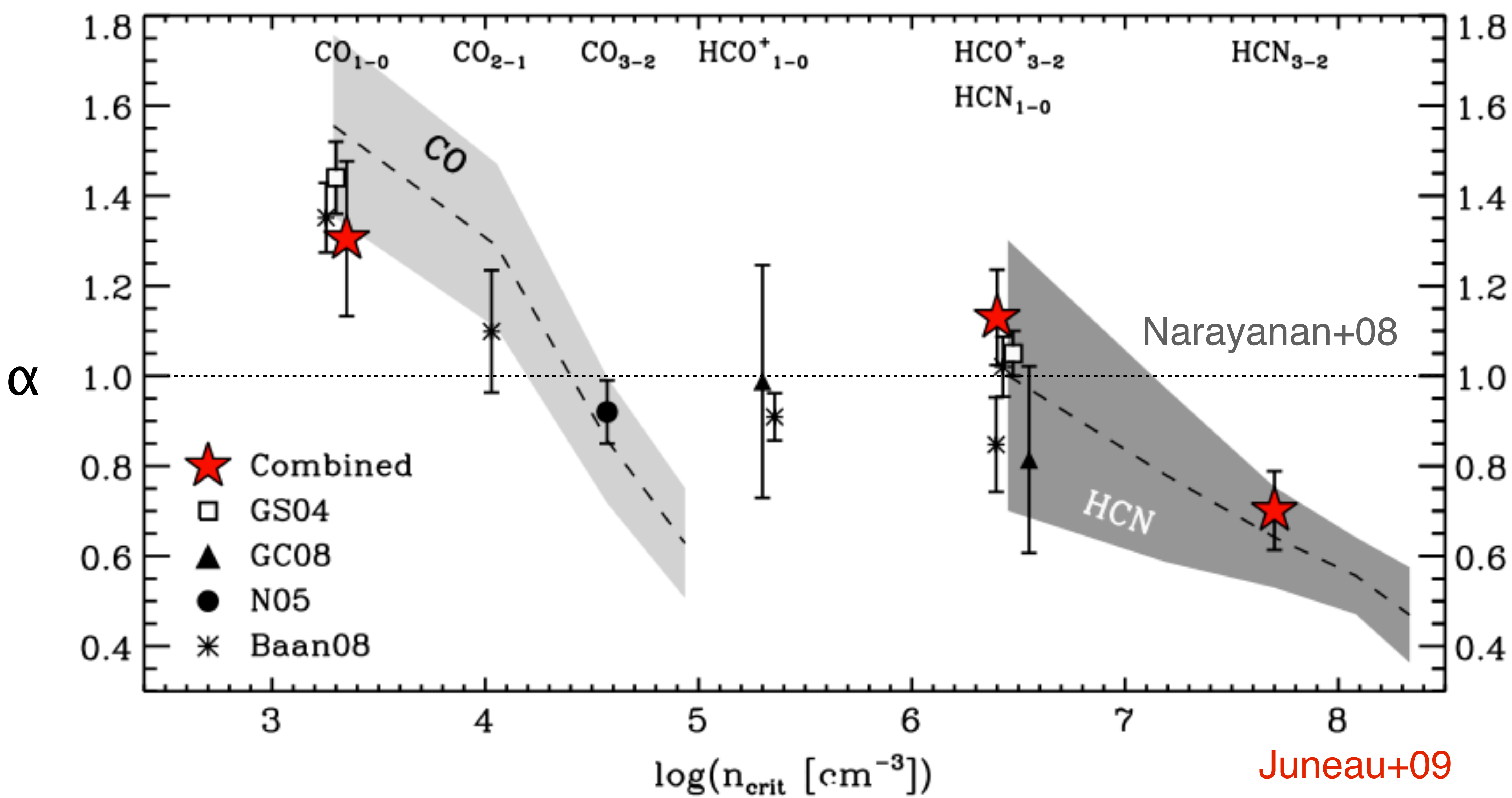


Juneau+09

Open questions

• what is the nature of the SF laws wrt the dense (>$10^4 cm^{-3}$) gas, i.e. the ISM phase that is actively forming the stars?

- *departure from linearity in the SF-law slope (α) ?*
- *changes in the normalization (β)?*
- *what determines α and β?*

• can we tie the observed SF laws to physical mechanisms governing/regulating star formation, and if so what are they?

• are the SF laws truly universal, i.e. are they the same on GMC-scales, entire galaxies at low- and high-z, different types of galaxies (disks, starbursts)?

Methodology

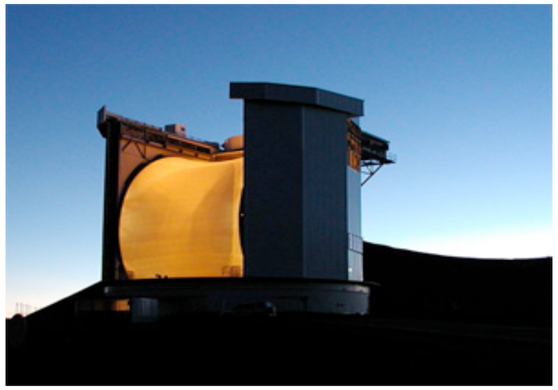
• we study the SF laws for the entire CO rotational ladder up to J=13-12 for a large, well-defined sample of local IR-luminous galaxies (U/LIRGs) as well as high-z dusty star forming galaxies (DSFGs)

• we also make use of recent SF law results inferred from heavy rotor molecules like CS and HCN (Zhang et al., 2014)

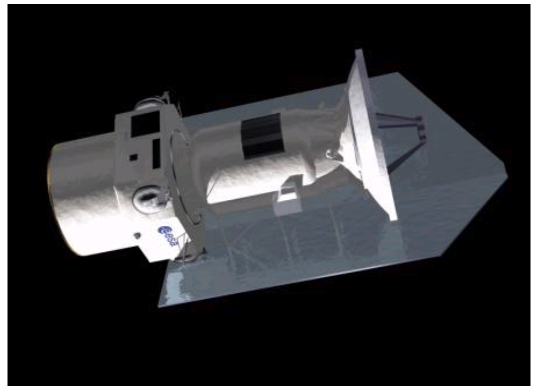
Zhang et al. (2014)
Greve et al., submitted

Observing the CO ladder in local (U)LIRGs

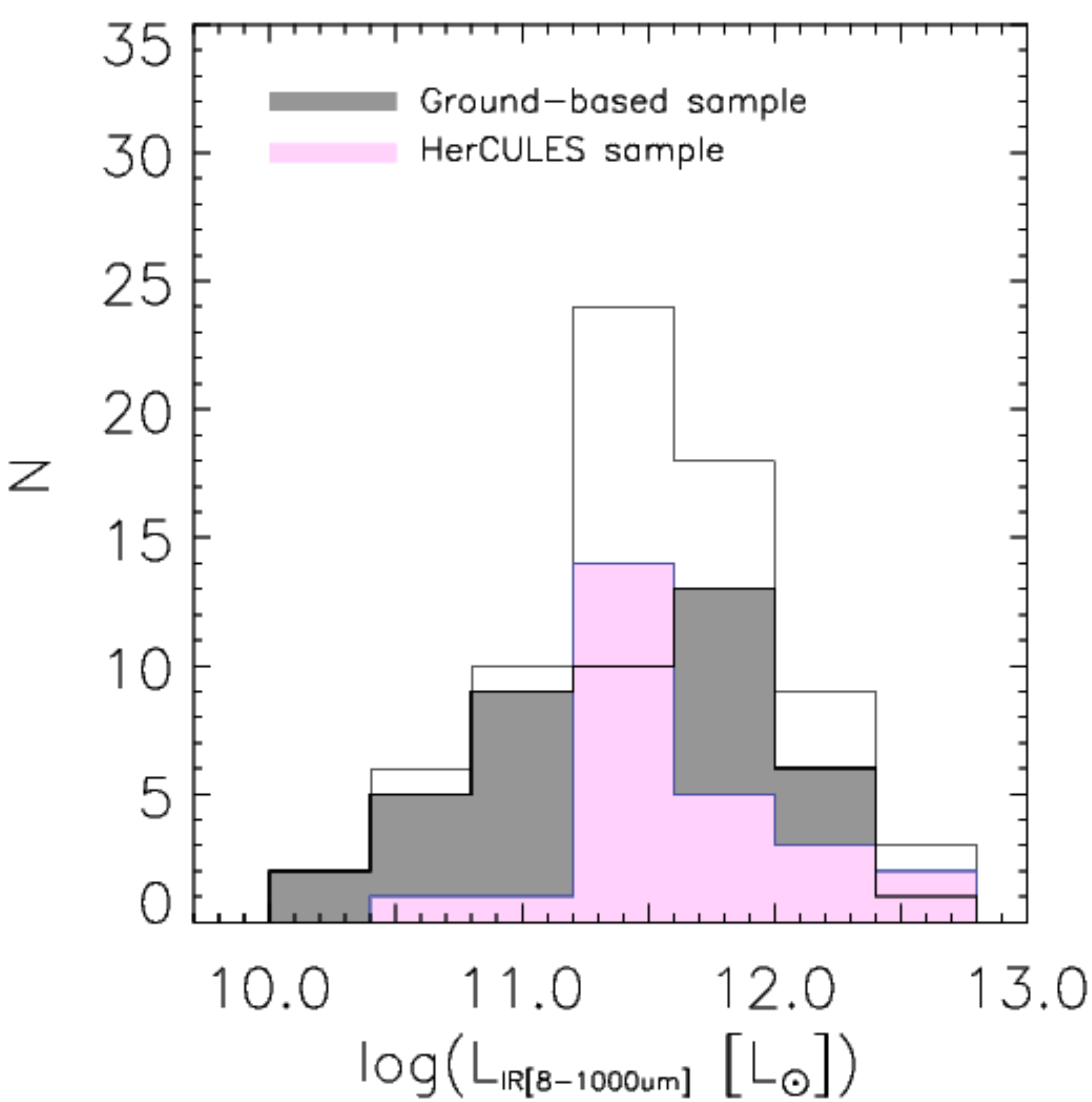
JCMT



Herschel



z < 0.1 (U)LIRG sample



<u>A Ground-Based Multi-Line Survey of local (U)LIRGs</u>

55 sources from IRAS BGS (z < 0.1):

- CO 1-0, 2-1, 3-2, 4-3
- HCN 1-0, 2-1, 3-2, 4-3
- HCO^+ 1-0
- CS 2-1, 3-2, 5-4, 7-6 (Zhang+14)

>350hrs. This is the largest multi-line survey to date + literature data. Papadopoulos+12

- Full CO rotational ladder, dense+FIR lines
- Comprehensive ISM characterization
- Disentangling Starburst vs. AGN

<u>Herschel Comprehensive (U)LIRG Emission Survey</u>

HERCULES (P.I.: van der Werf).

29 sources from IRAS BGS (z < 0.1):

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- [CI] 369μm and 609μm
- H_2O lines

100hrs. van der Werf+10

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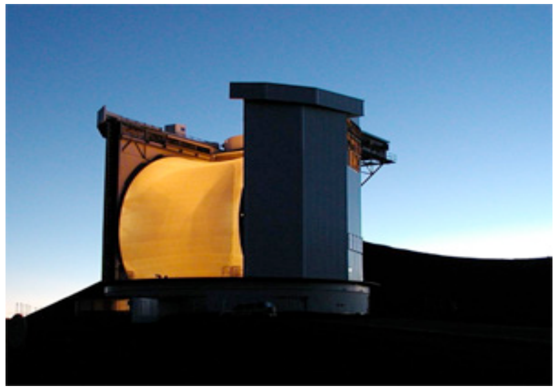

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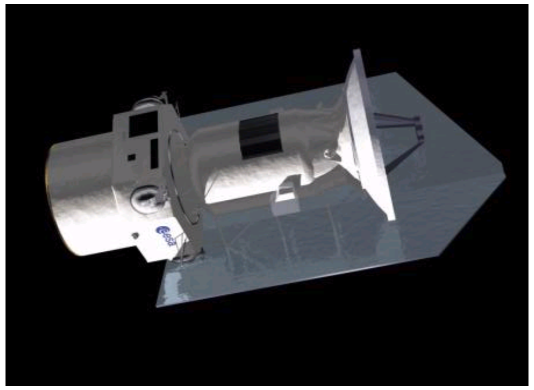
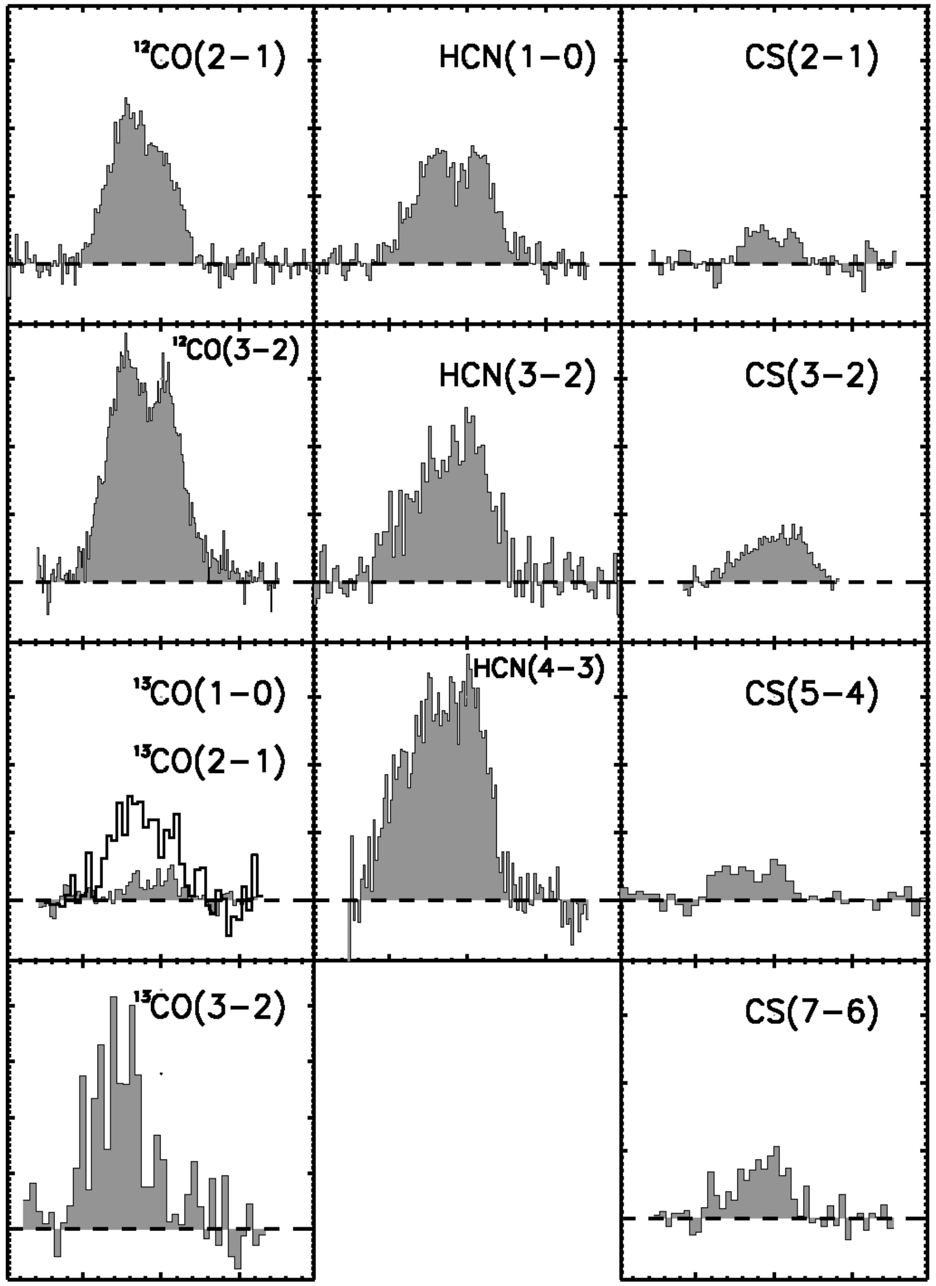


Molecular lines observed in NGC6240



Greve et al. (2009)

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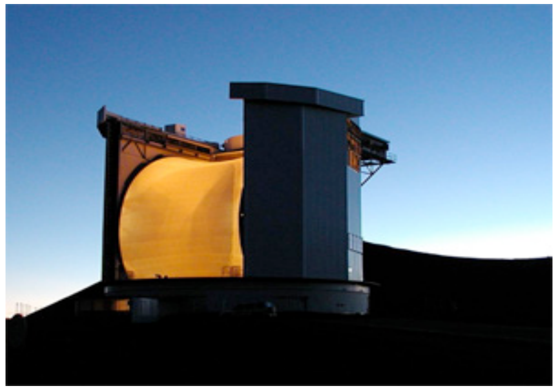

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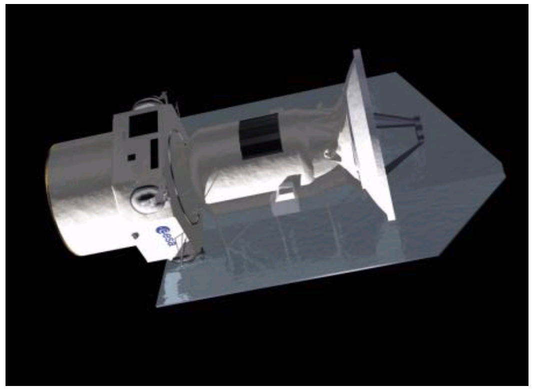

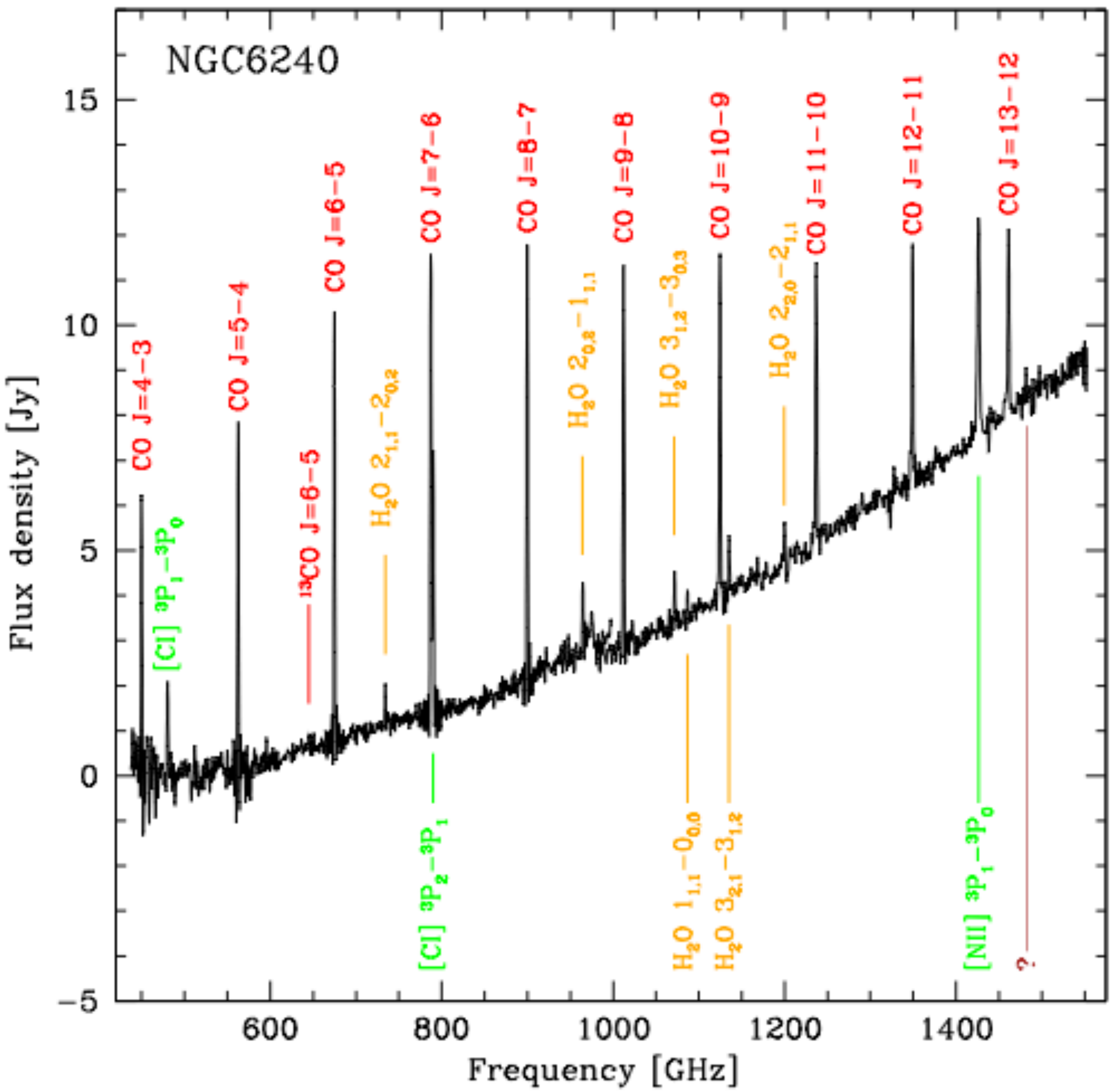

Papadopoulos et al., accepted; Zhang et al., in prep.

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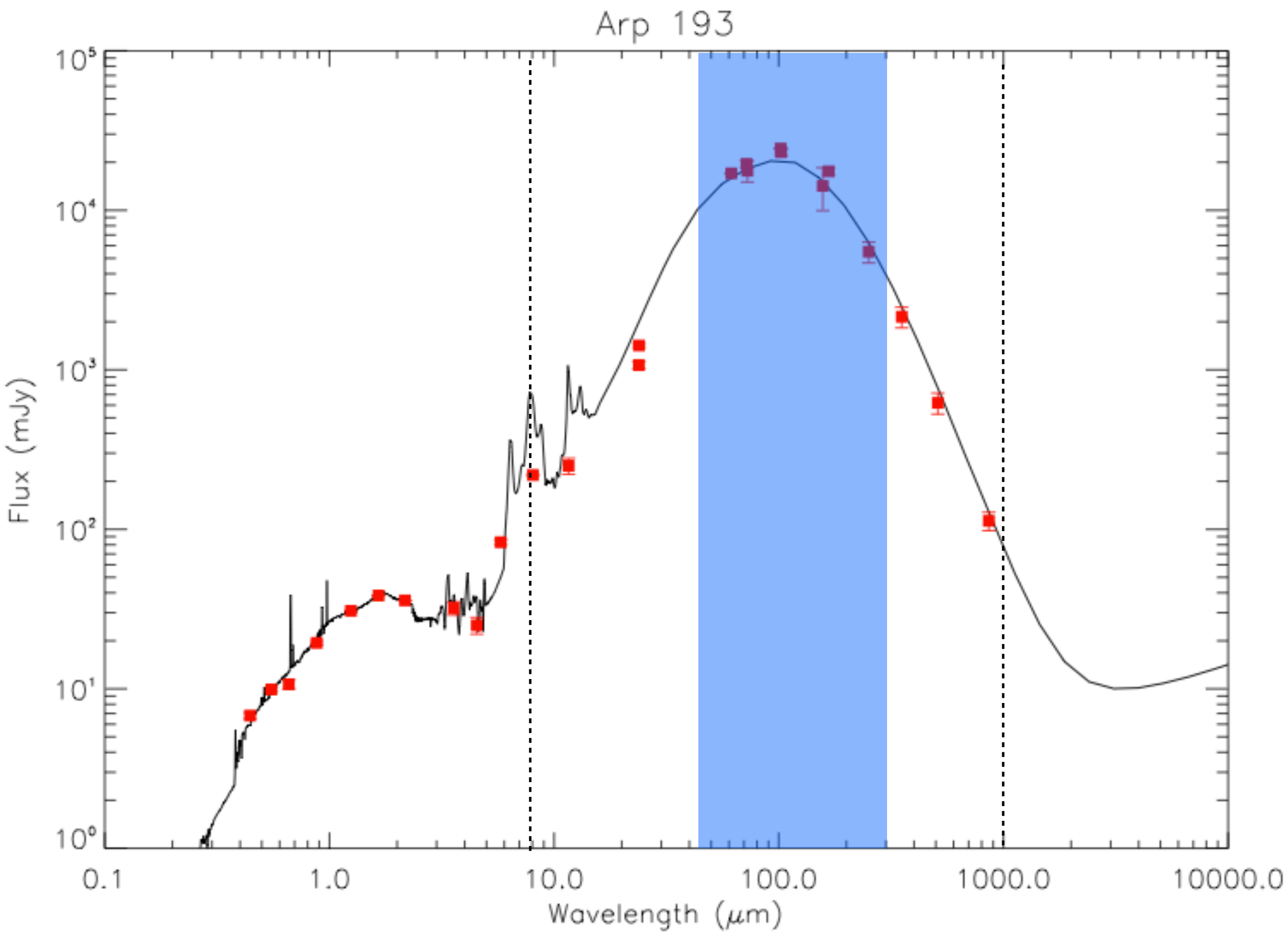
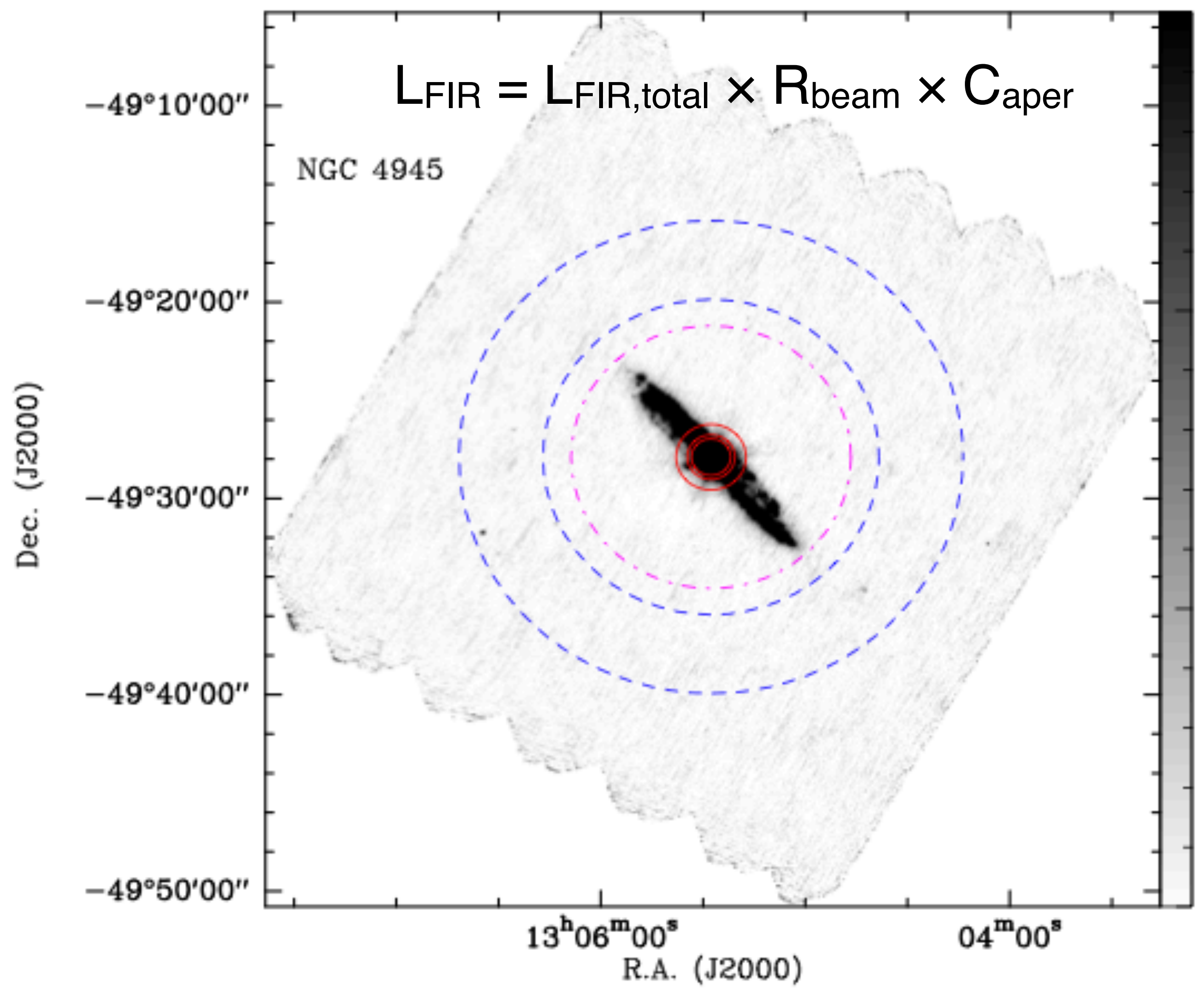
SEDs and L_{IR} of local (U)LIRGs

- Compilation of pan-chromatic continuum data (optical, mid-IR, PACS+SPIRE, IRAS,…)
- SED fitting with modified CIGALE (Burgarella+05) using Chary & Elbaz+01 and Dale & Helou+02 templates
- We adopt FIR (50-300μm) luminosities (clean compared to 8-1000μm) (but no differences…)

- Is CO - IR beam-matching an issue? NO
- SPIRE-FTS beam FWHM range ~16”-42”
  Ground-based FWHM range ~11”-14”
- (U)LIRGs are generally compact (<8”). We have CO(1-0)/IR/cm sizes for all our sources - all within the CO beams (Papadopoulos+12)
- For sub-LIRG sources beam-correction is crucial!





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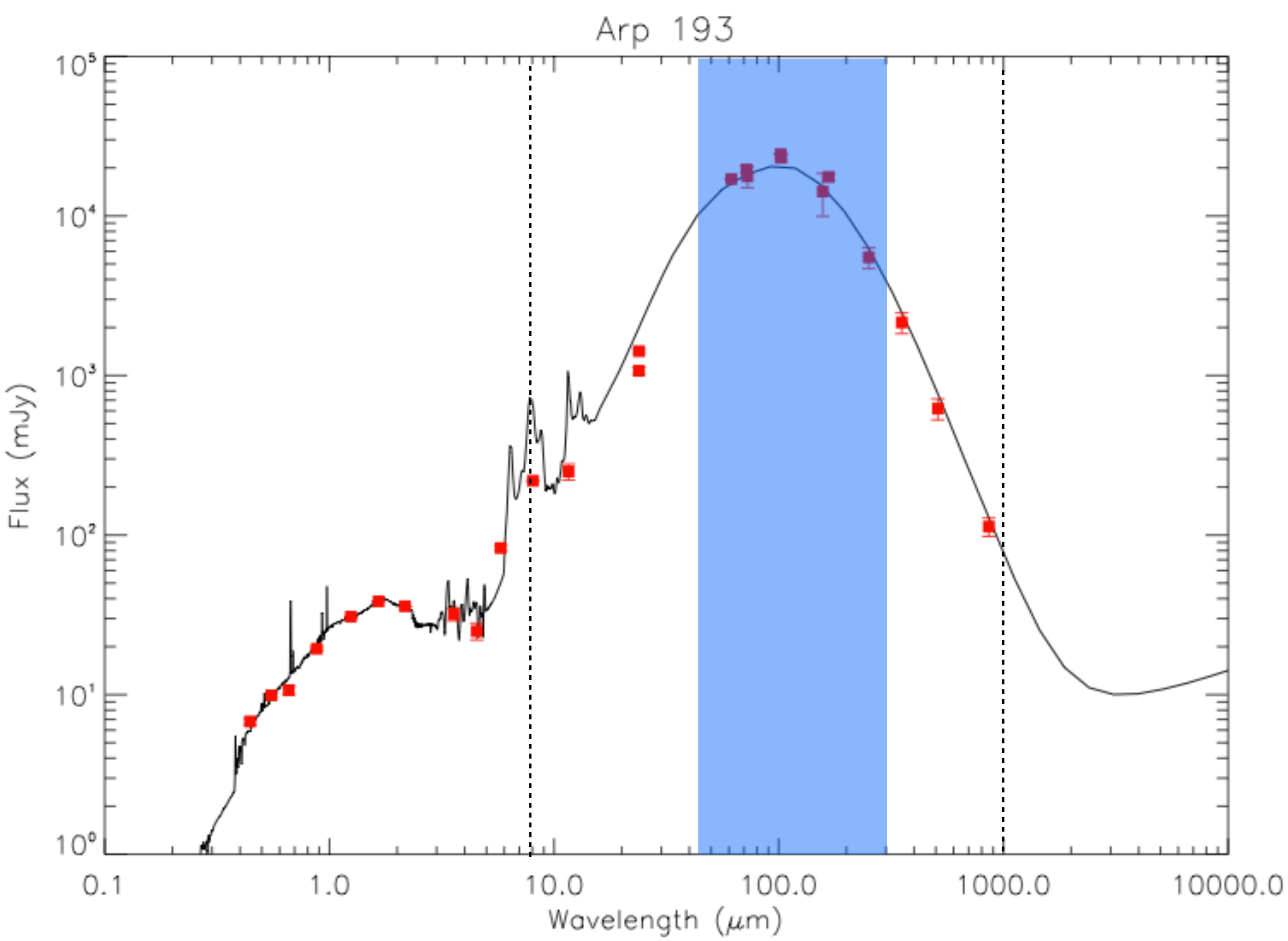

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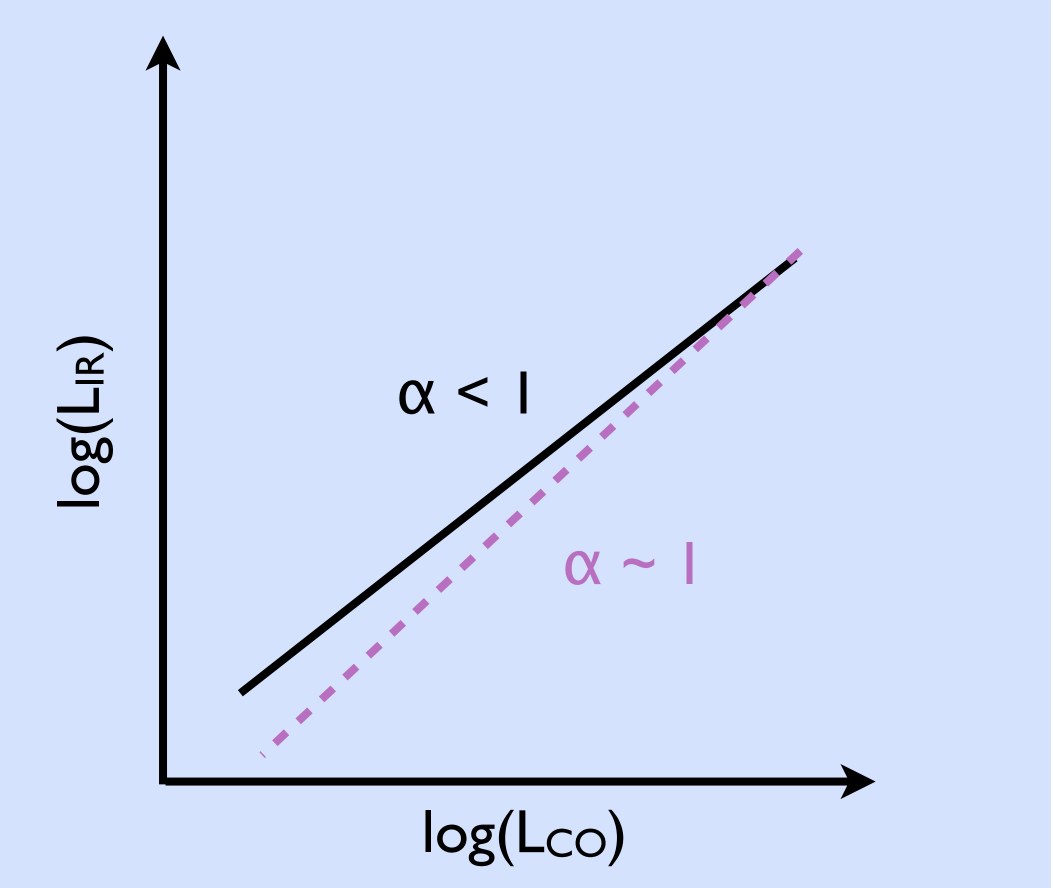


Observing the CO ladder in high-z (U)LIRGs

Dusty Star Forming Galaxies (DSFGs):

• A compilation of all (sub)mm-selected $z > 1$ DSFGs with CO line detections.

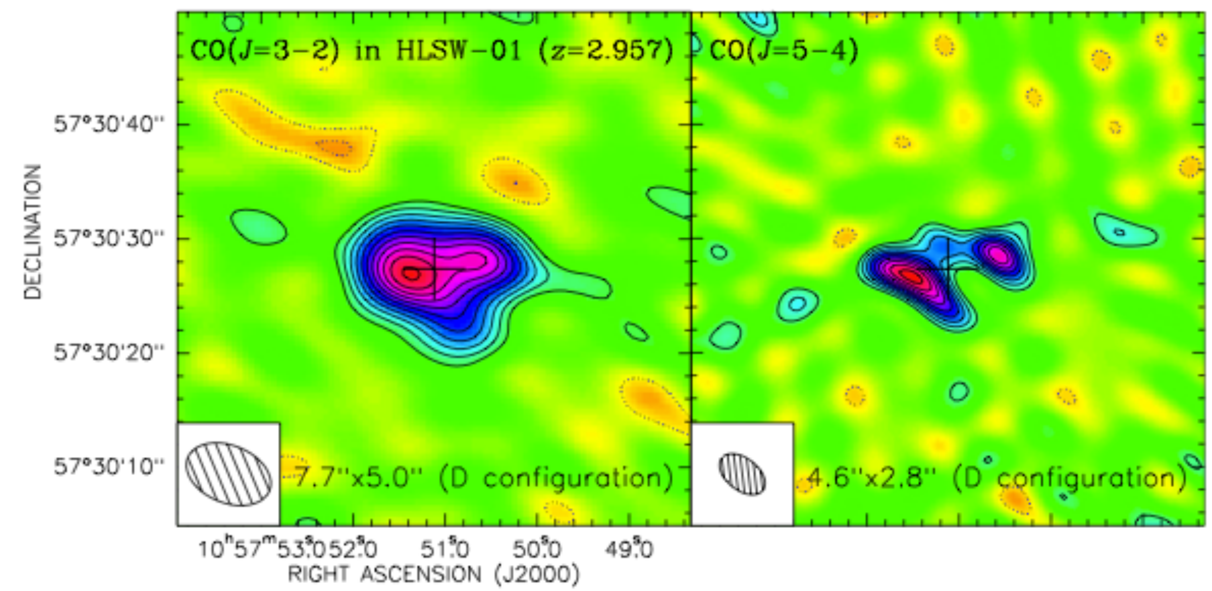
• Obvious AGN discarded

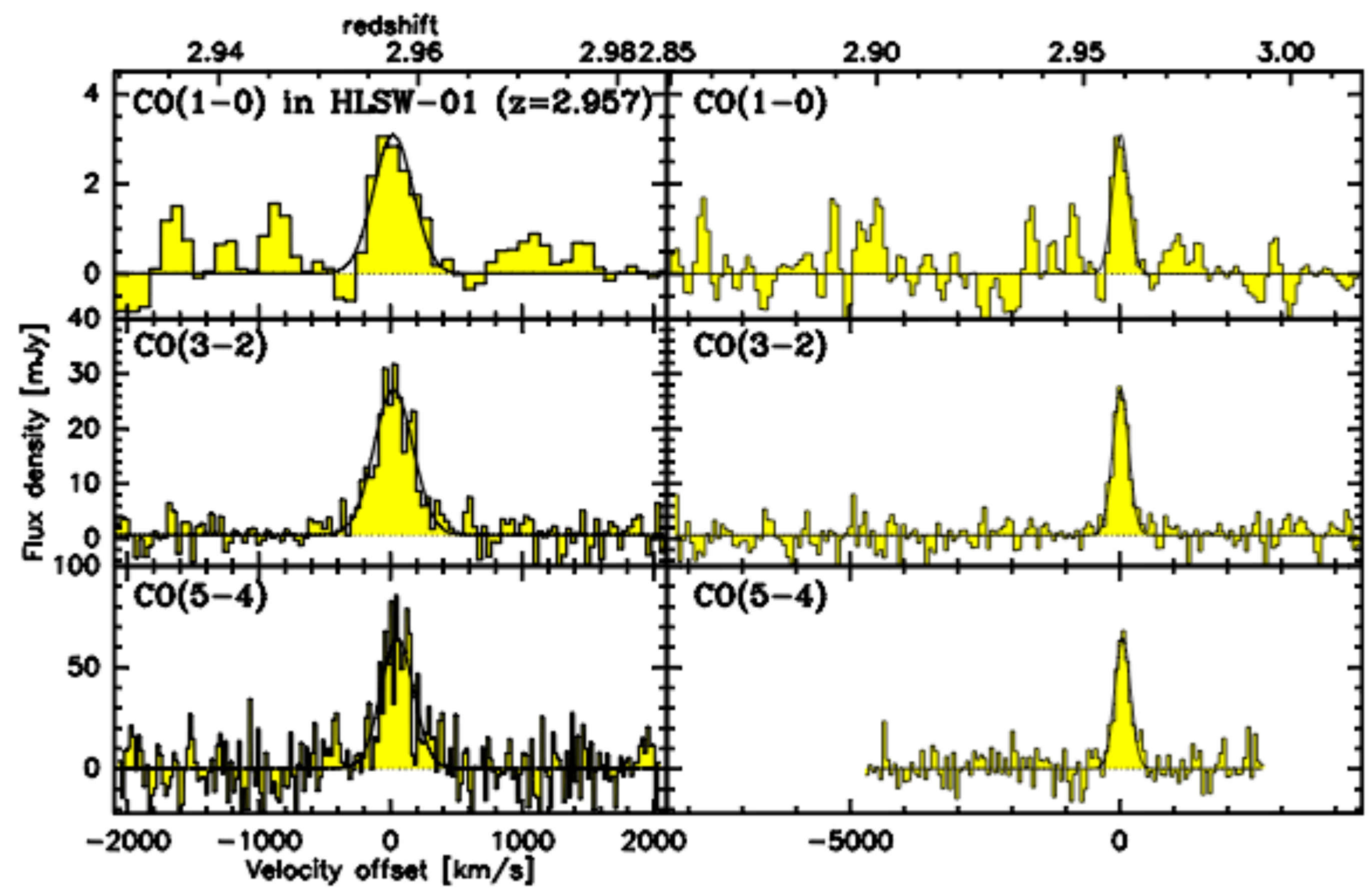
• Multiple observations of the same CO transition were averaged, and intrinsic line luminosities re-calculated

• A total of 59 unlensed DSFGs and 17 lensed DSFGs (published as of Jan 2014)

• ~1.5 decades worth of work!

HERMES J105751.1+573027 z=2.95





Frayer+98+99; Neri+03; Greve+05; Tacconi+06,+08; Hainline+06; Riechers+09+13; Ivison+11; Bothwell+11+13; Carilli+09+12 etc etc

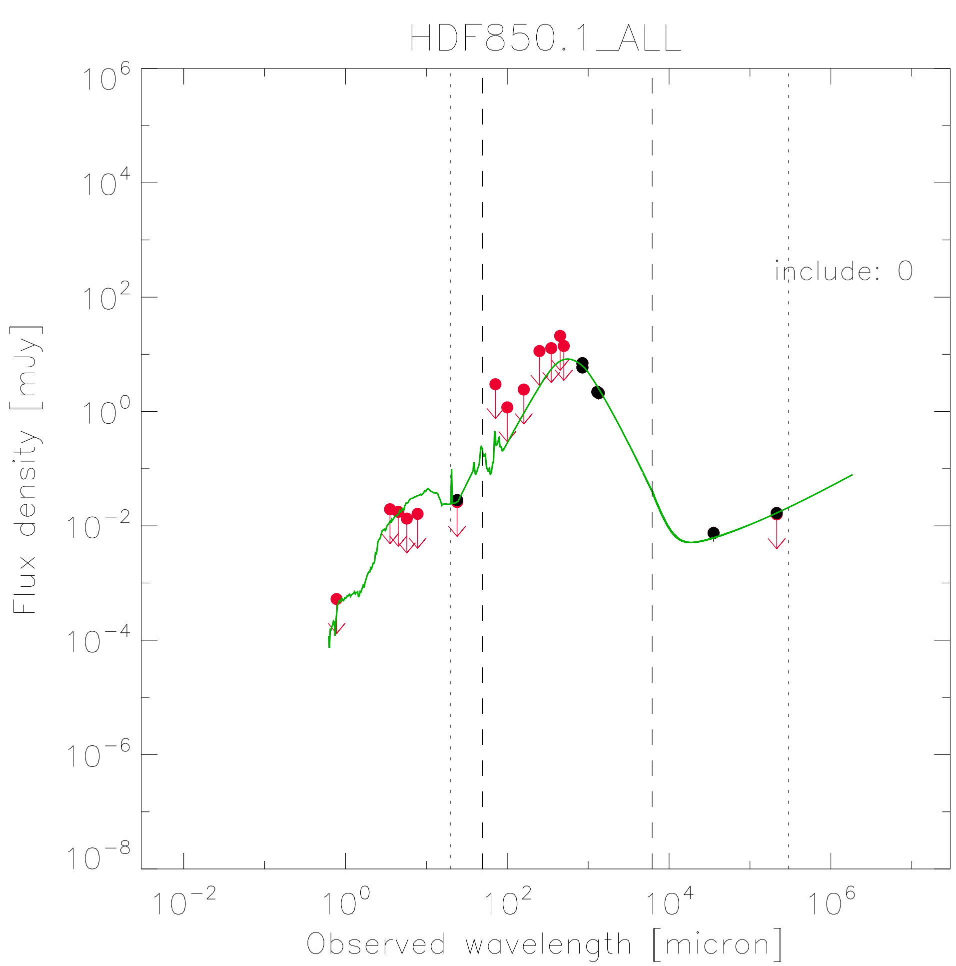
SEDs and L_{IR} of high-z DSFGs

- Painstaking effort to collect pan-chromatic continuum data

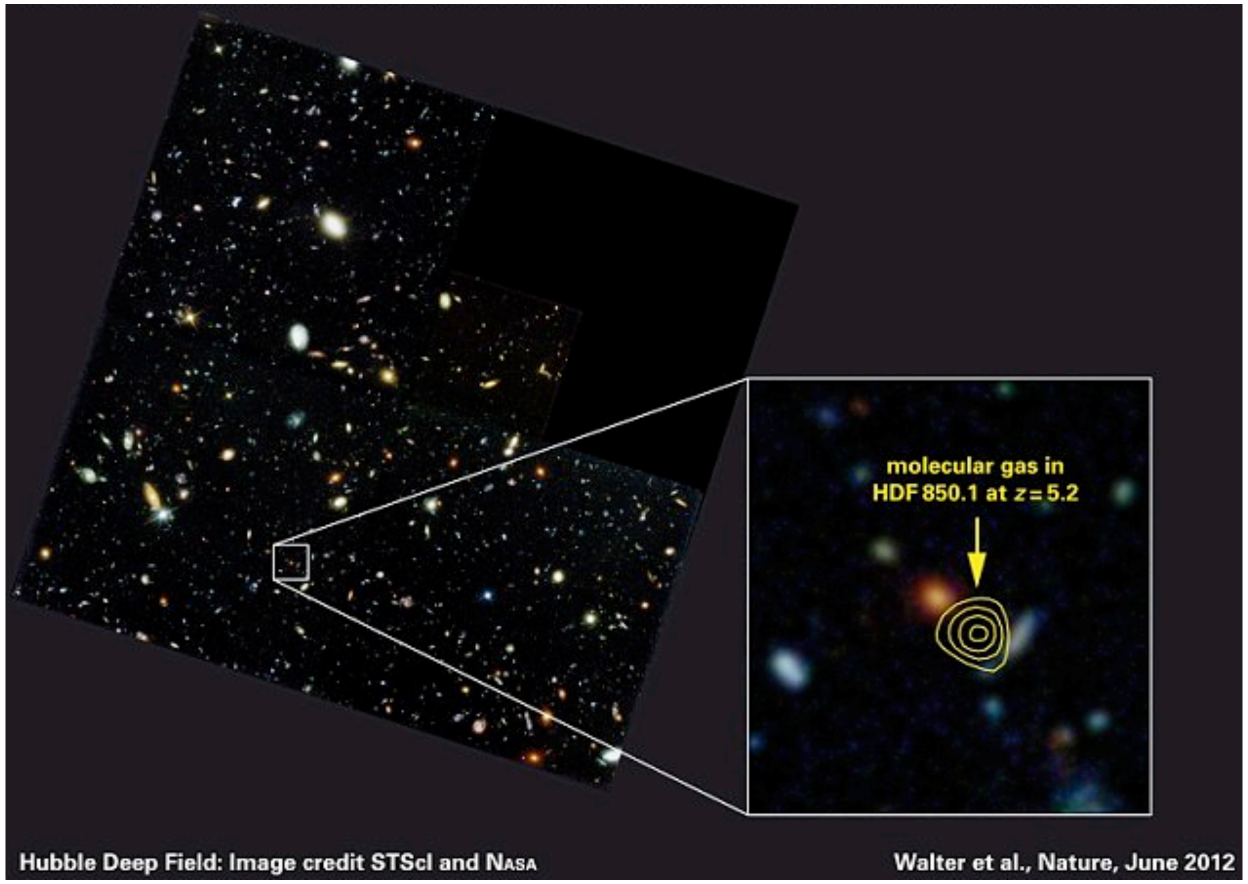
- CIGALE fits, identical to local (U)LIRG fits

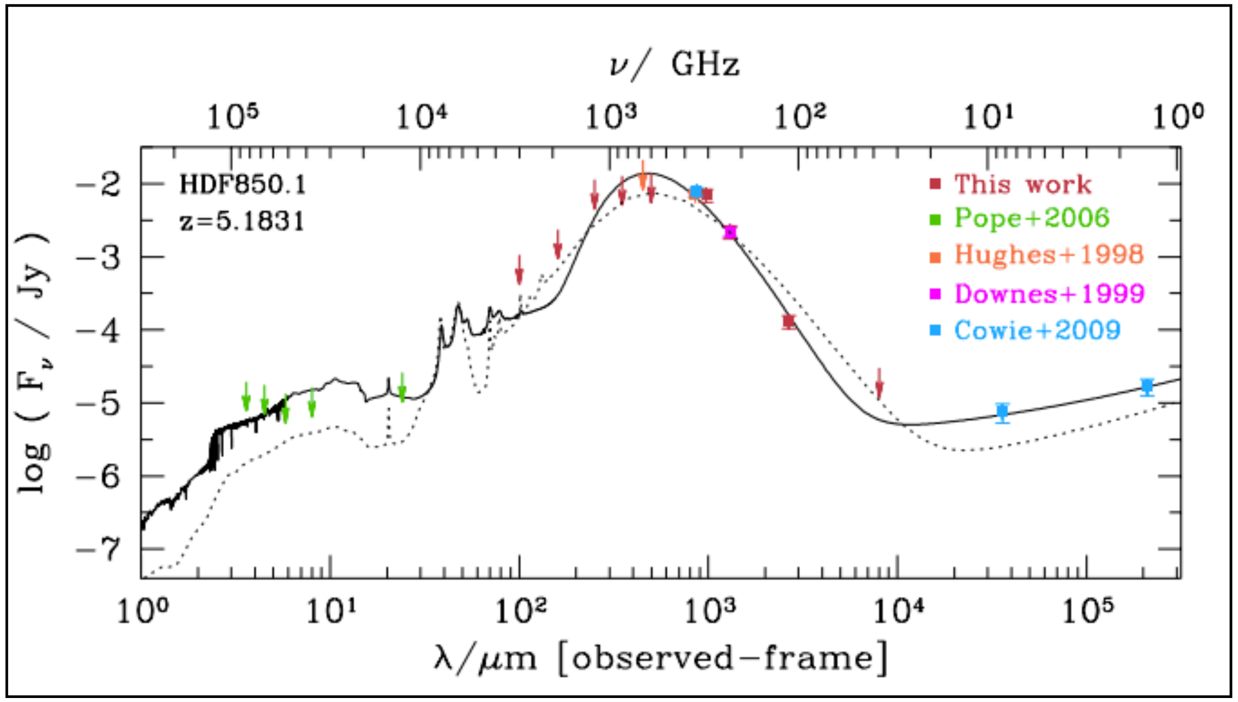
- Only sources with >3 FIR/submm data points across the dust peak, and with good overall CIGALE fits were included in the analysis

- **Final sample: 49 DSFGs (lensed+unlensed)**



Finding the correct counterpart can be a nightmare...





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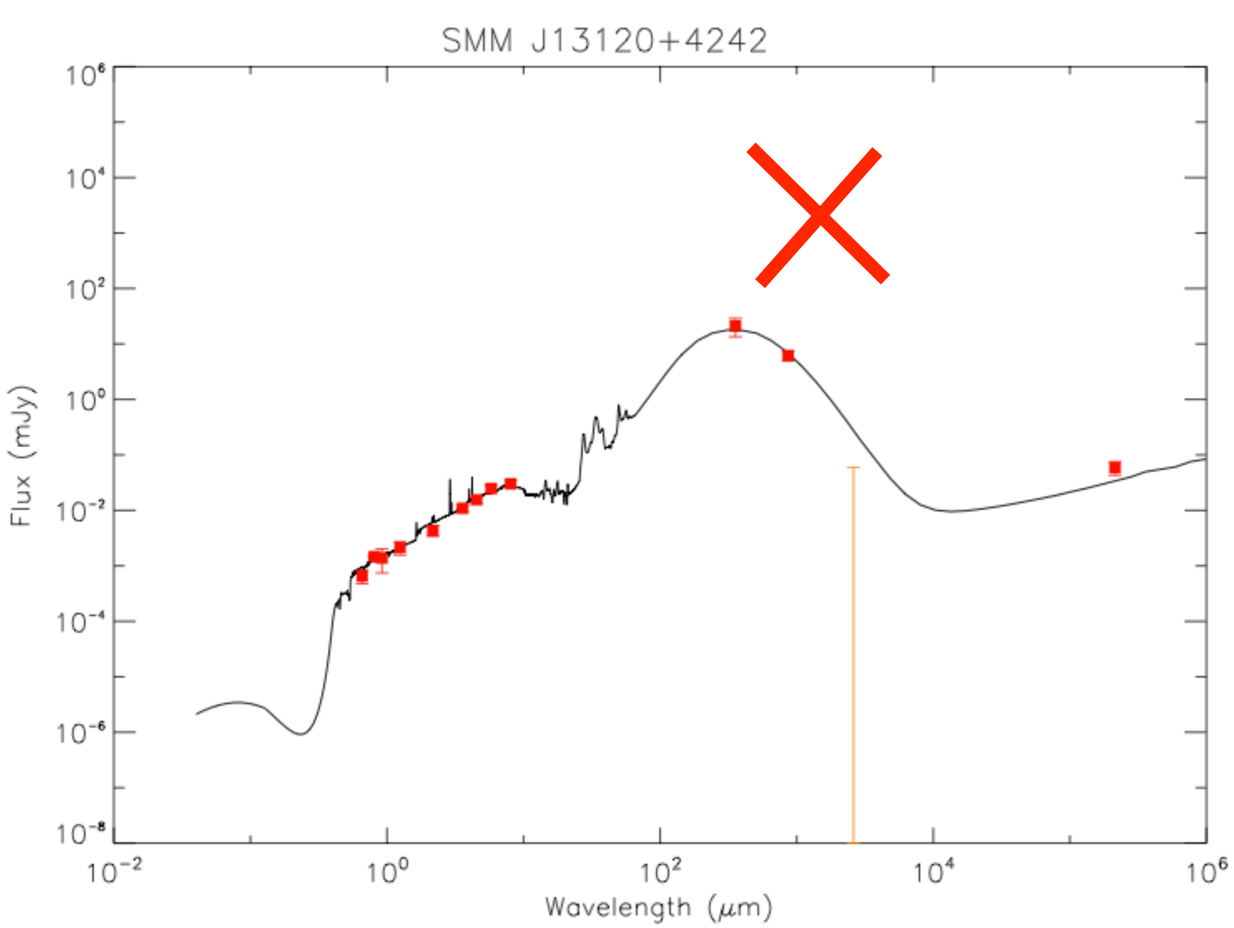

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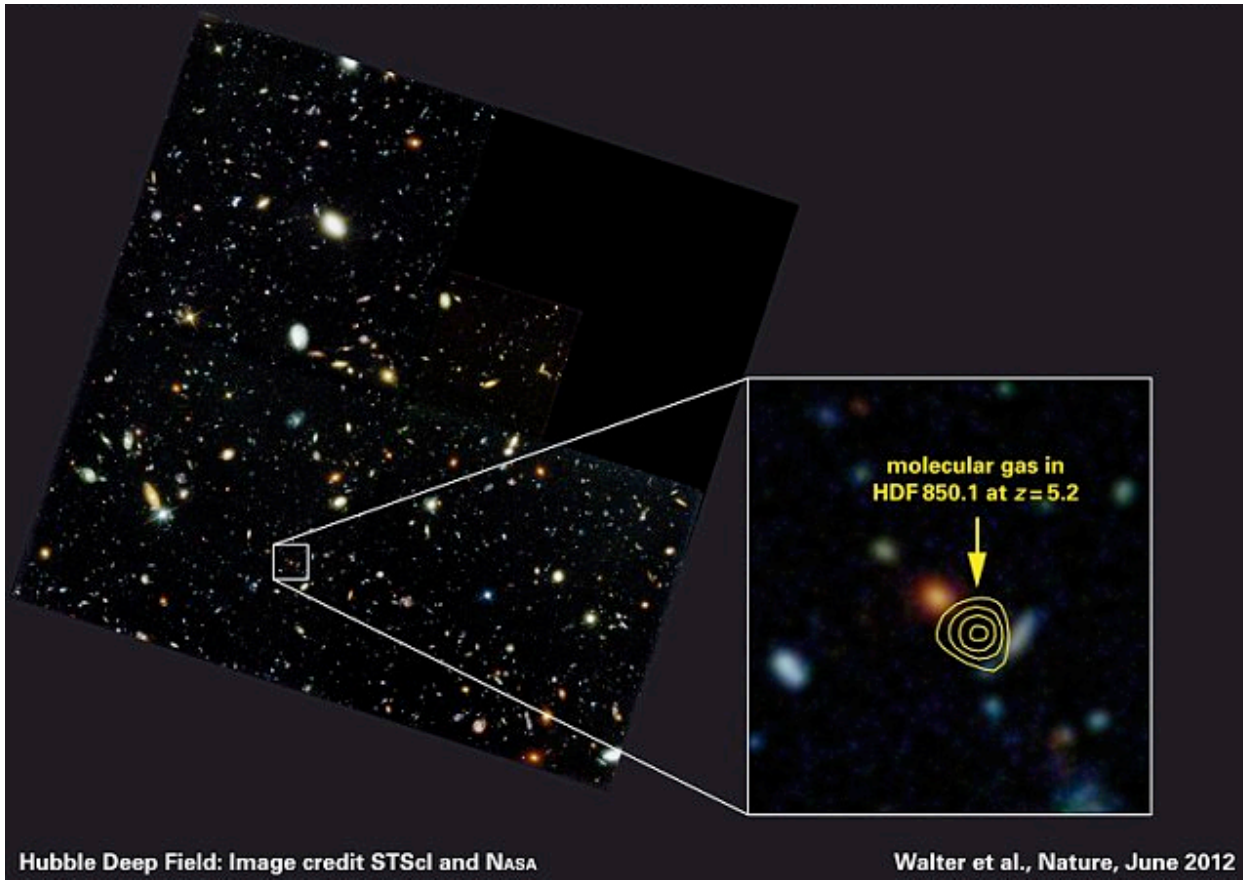

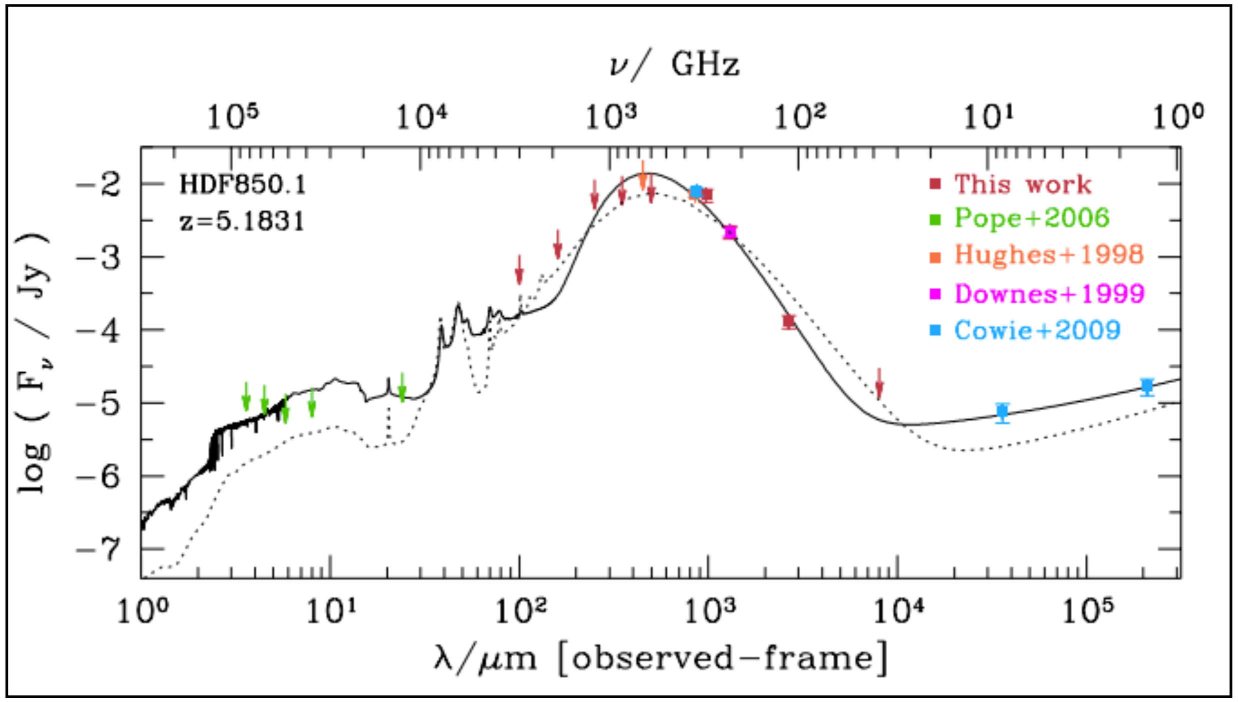

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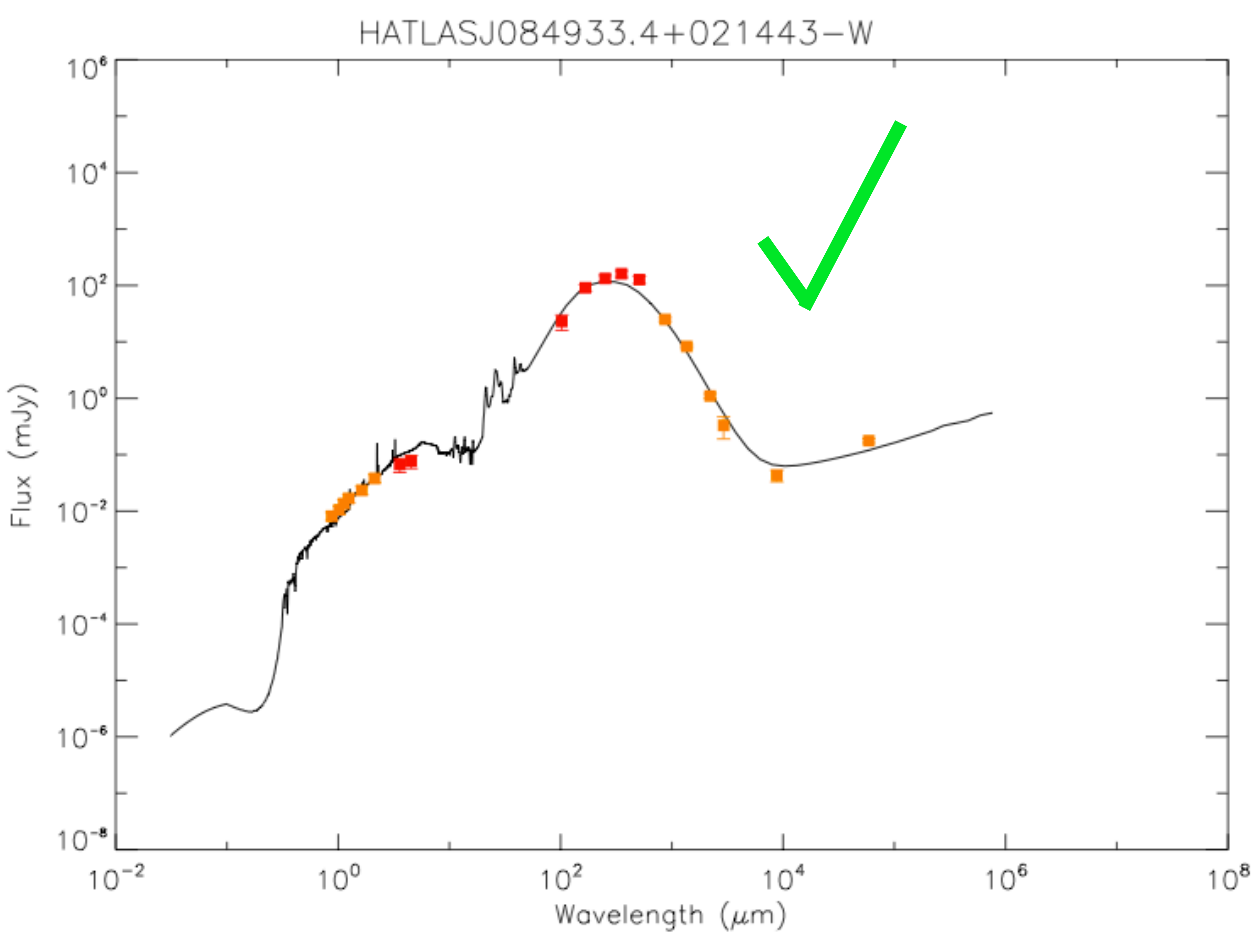

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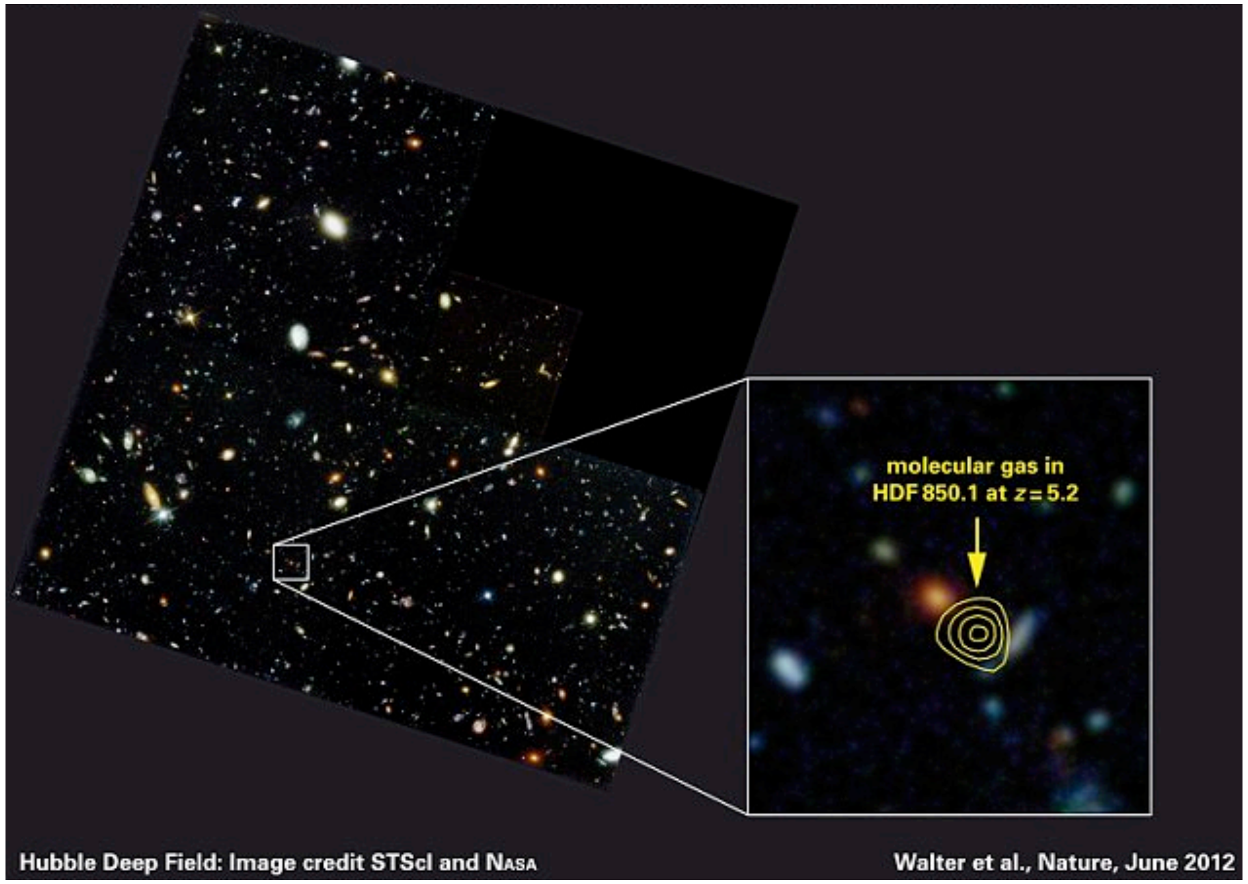
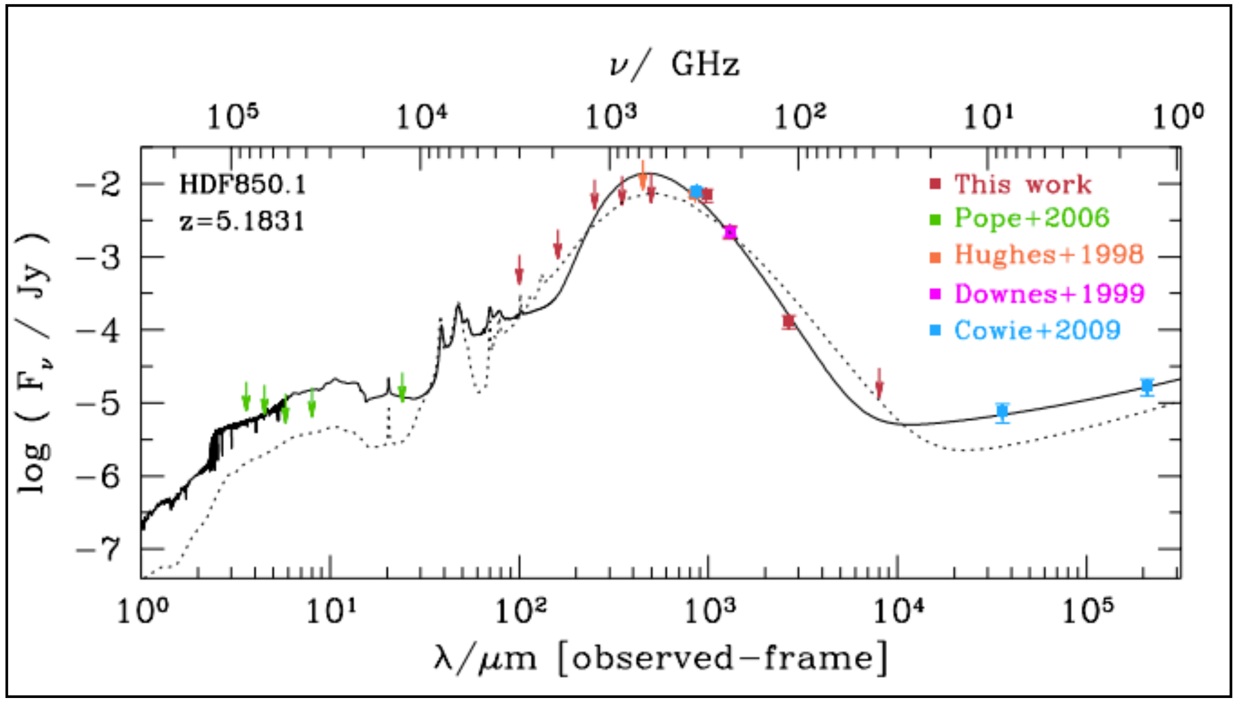
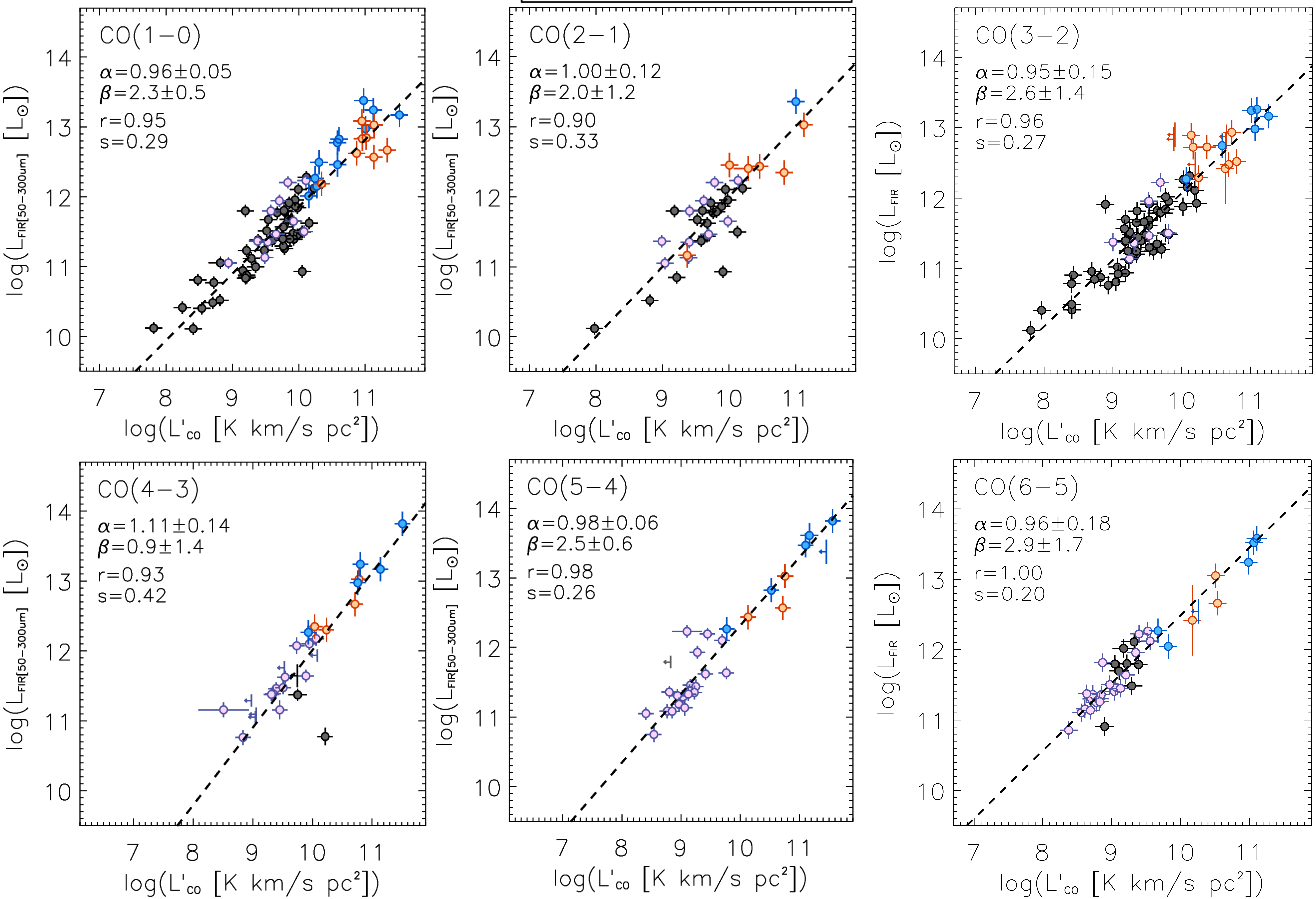




L_{IR}-L_{CO} relations

Greve, in submitted.



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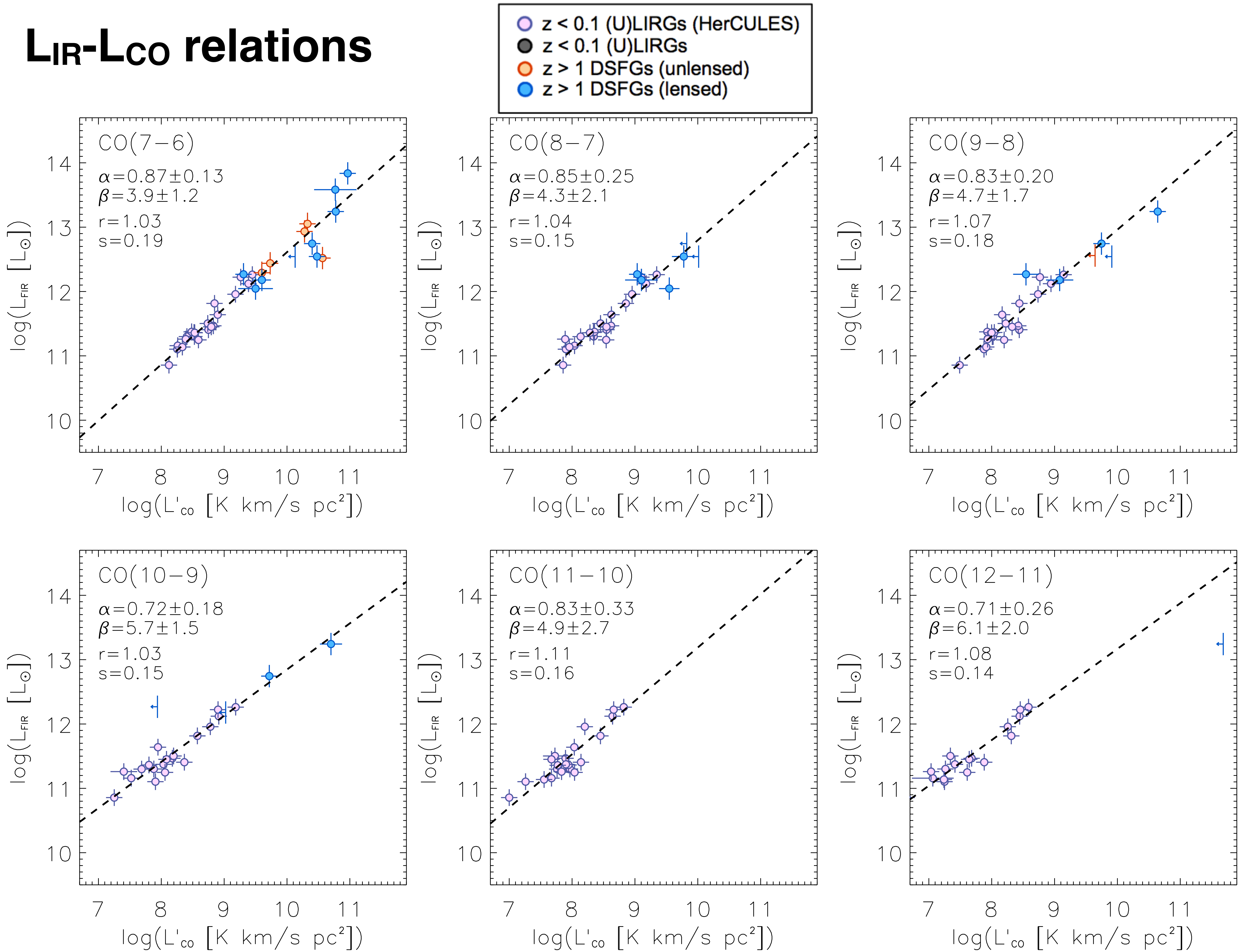
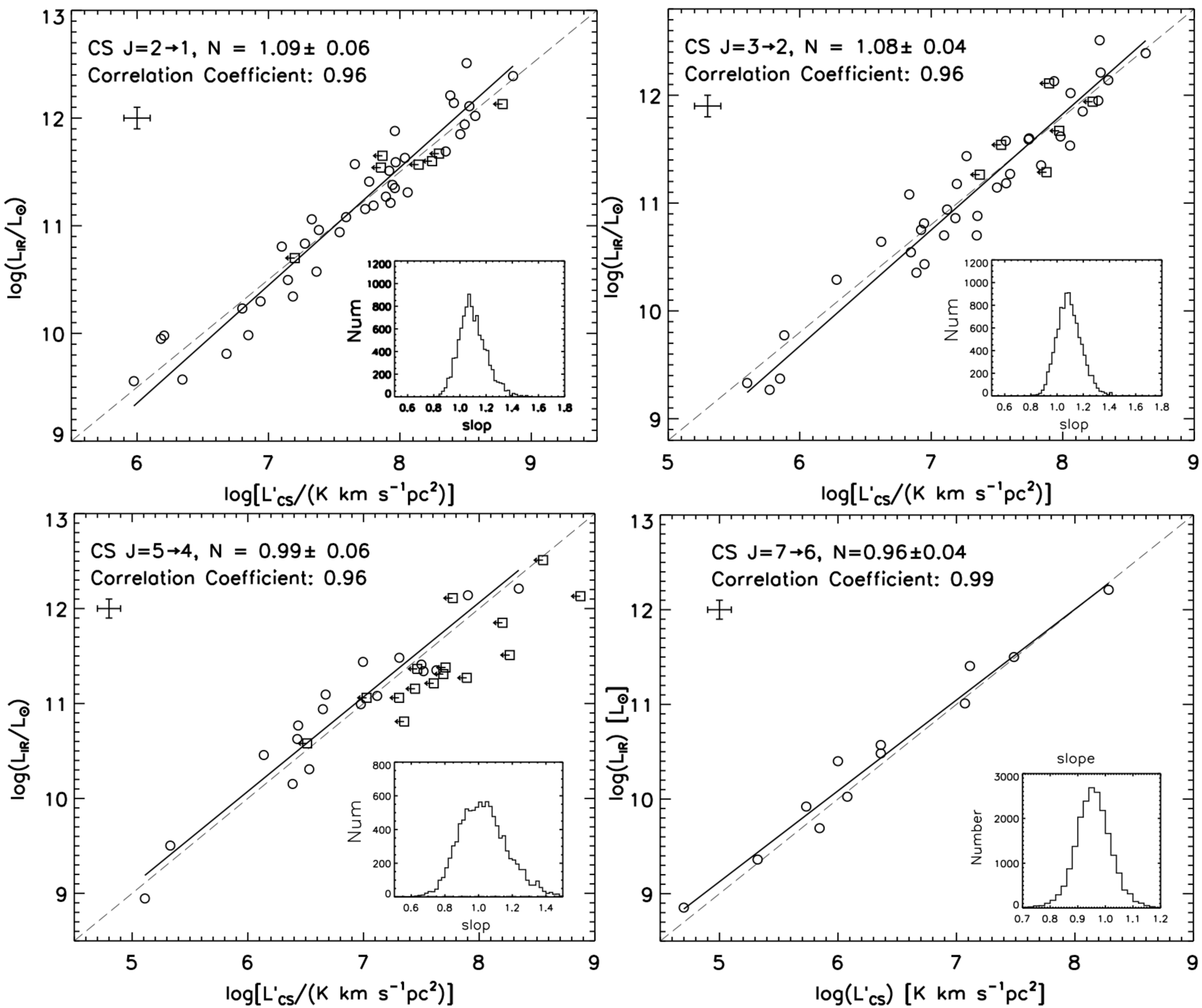


L_{IR}-L_{CS} relations

Zhang et al. (2014)



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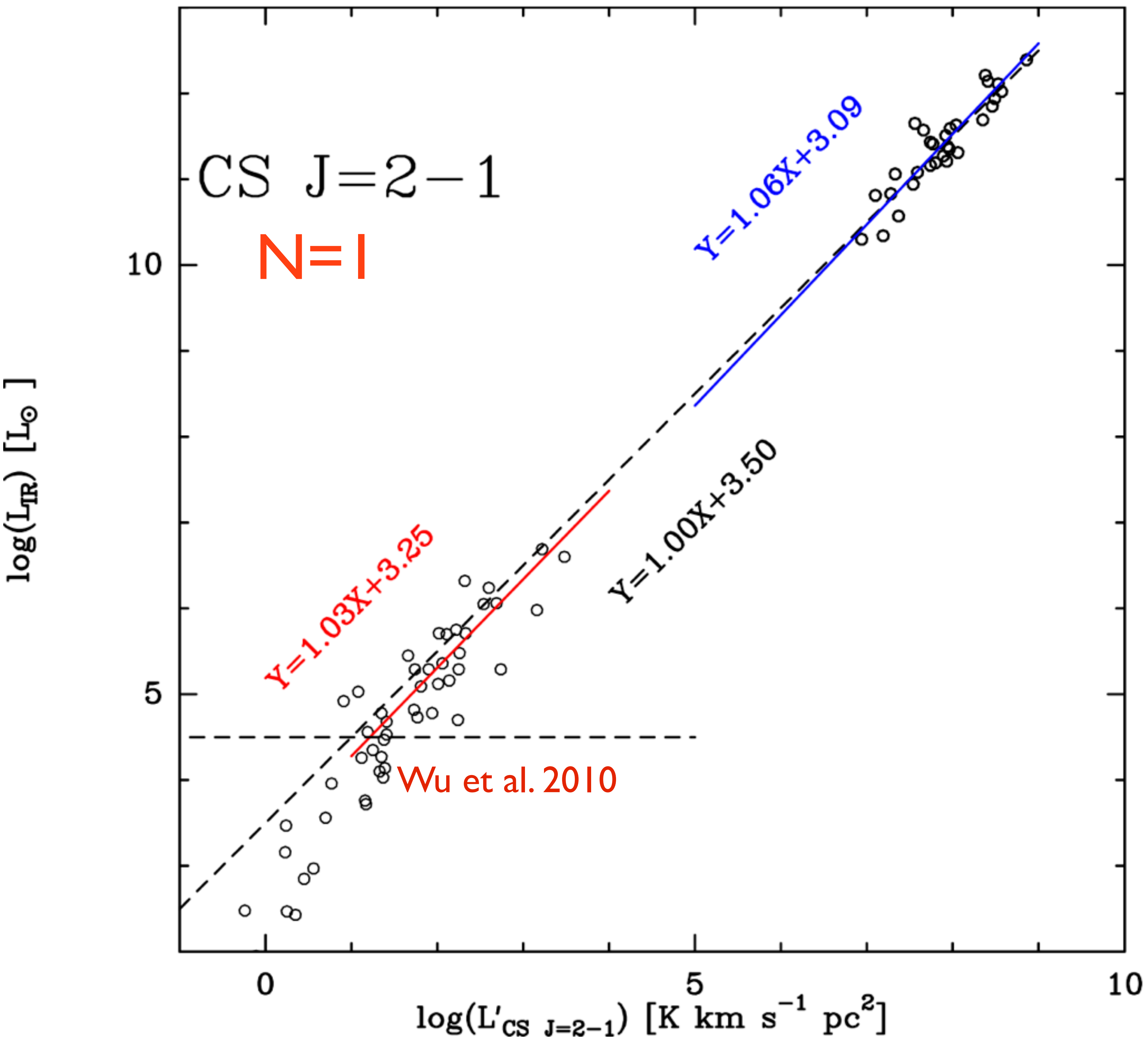

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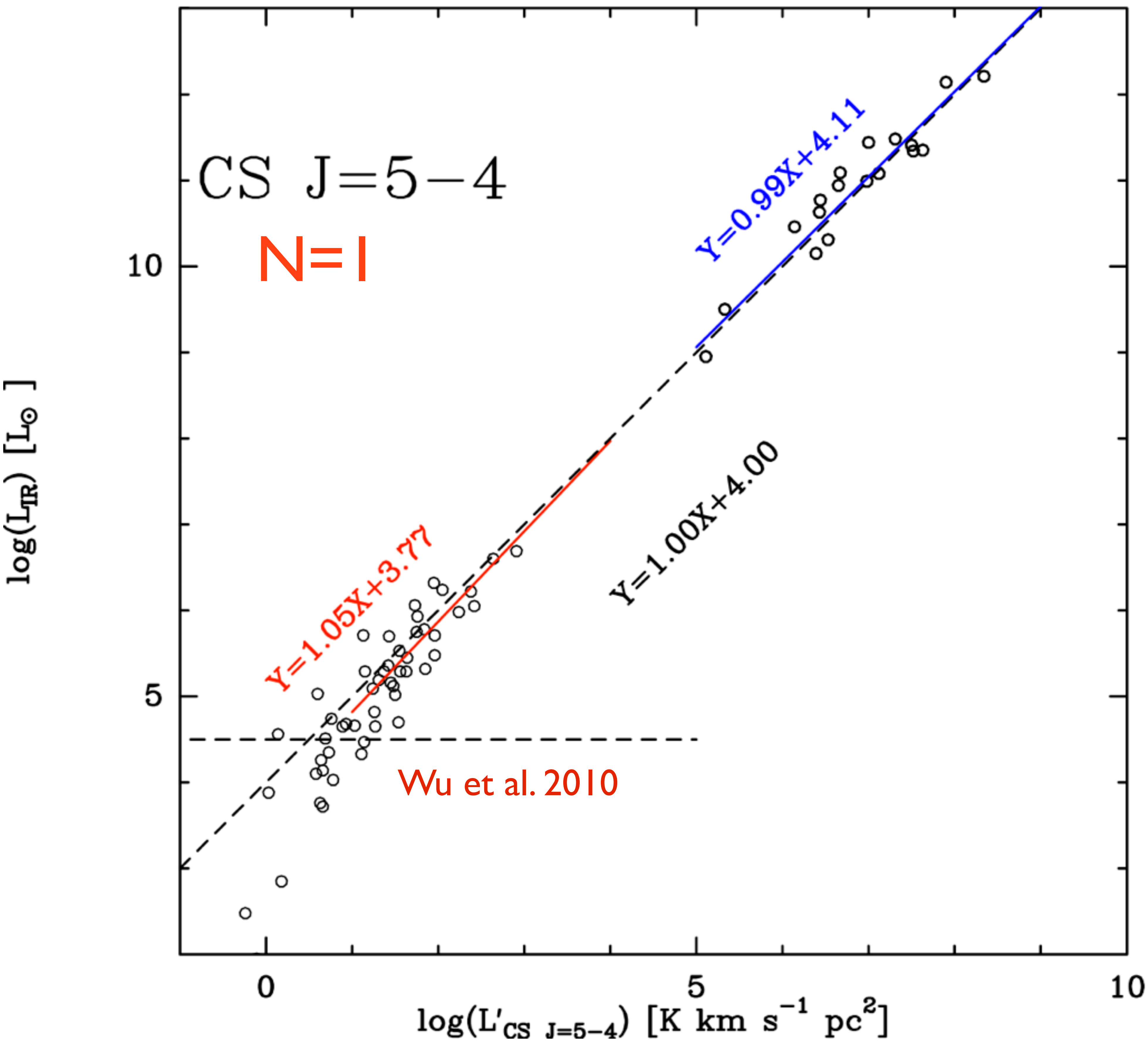

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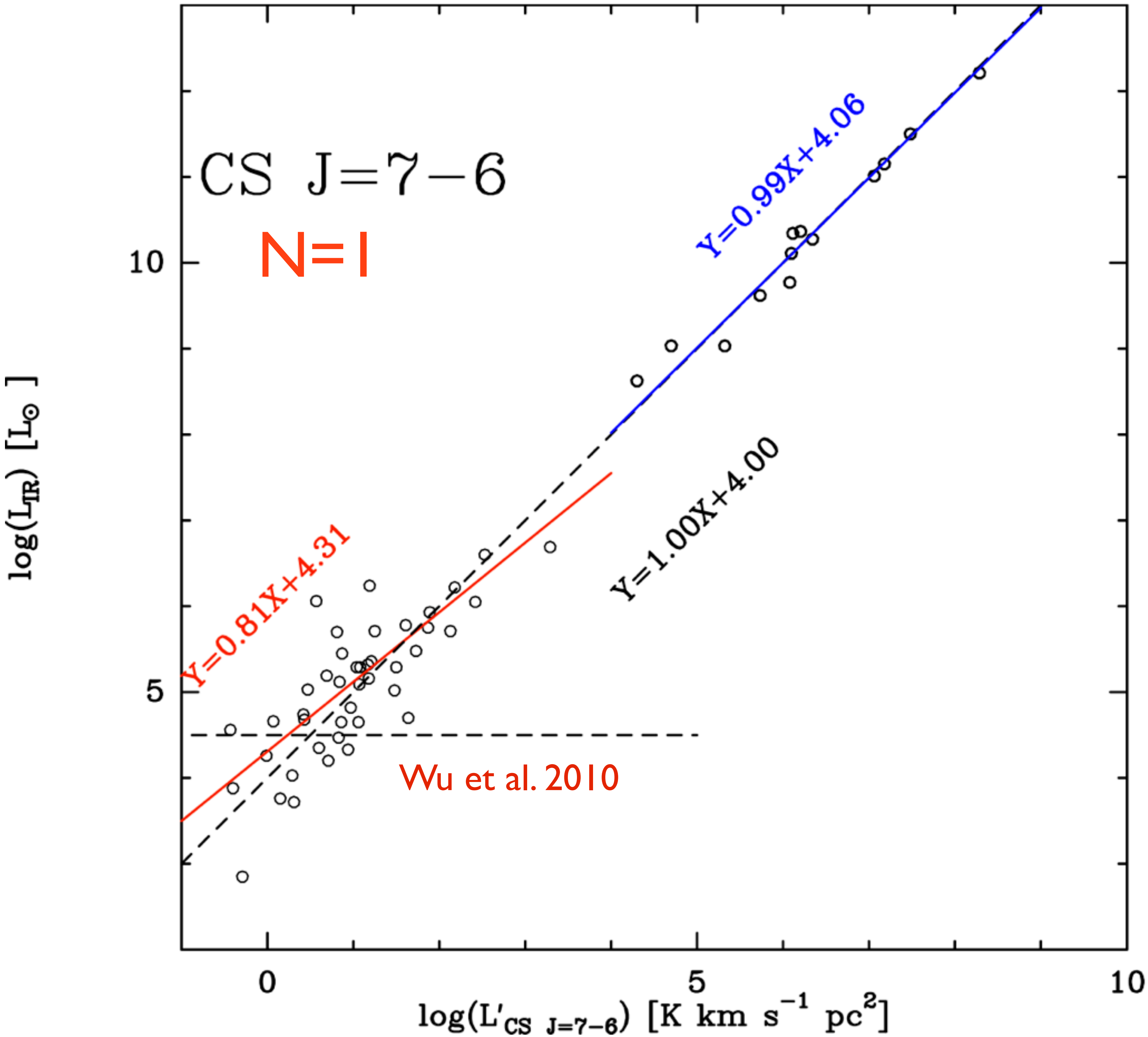
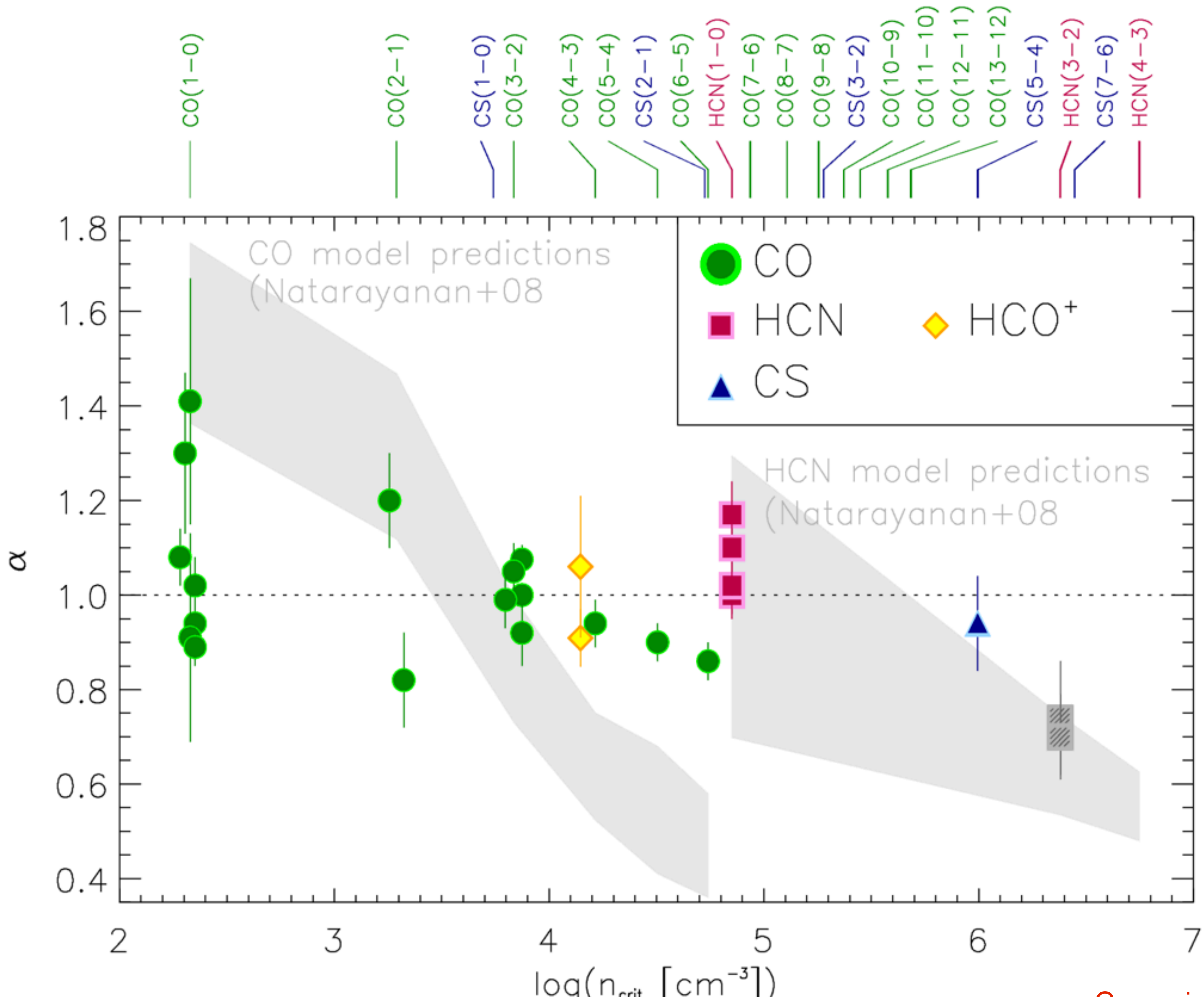


L_{IR}-L'_{mol} slope vs. n_{crit}(mol)



Greve, in submitted.

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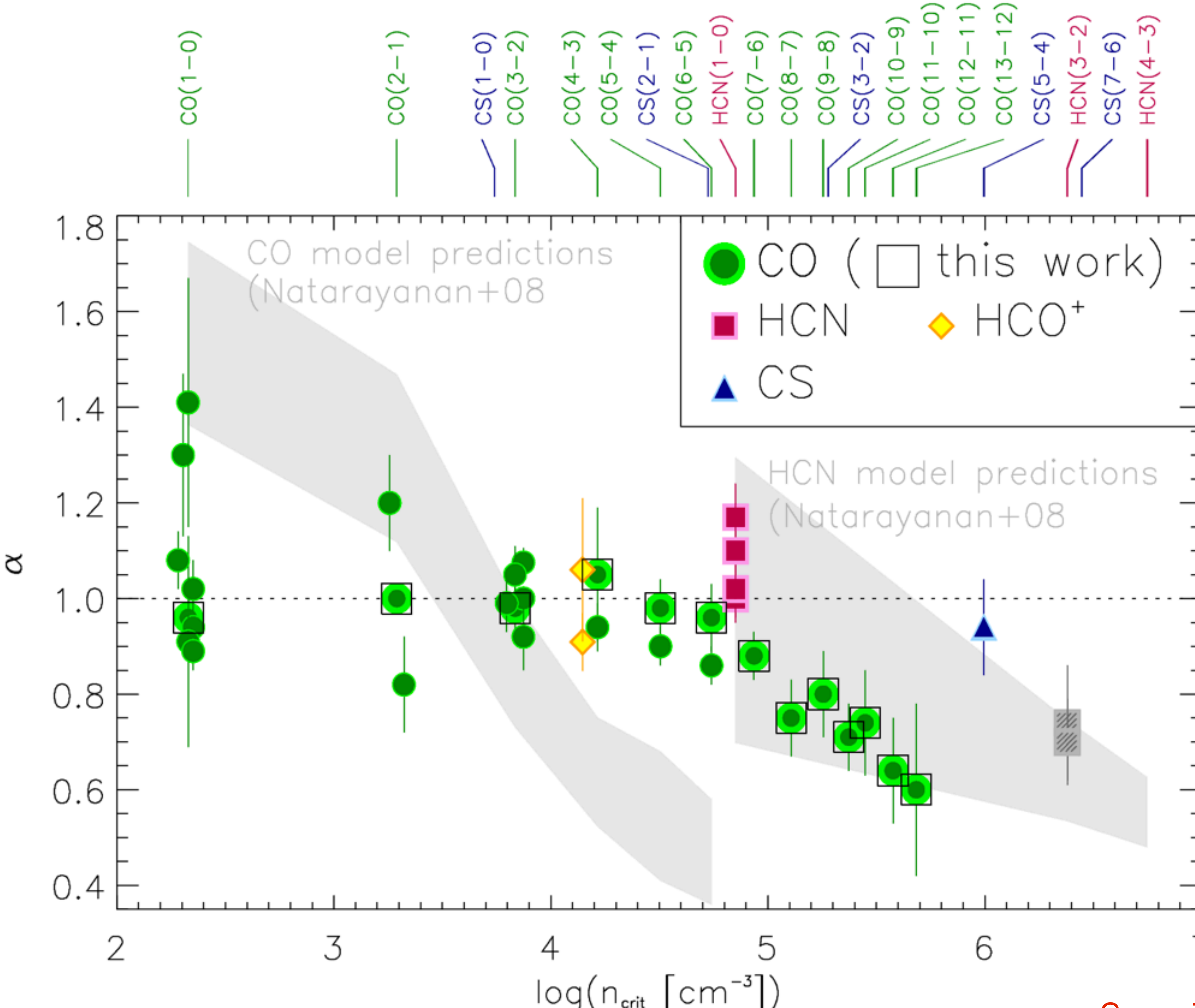

Greve, in submitted.

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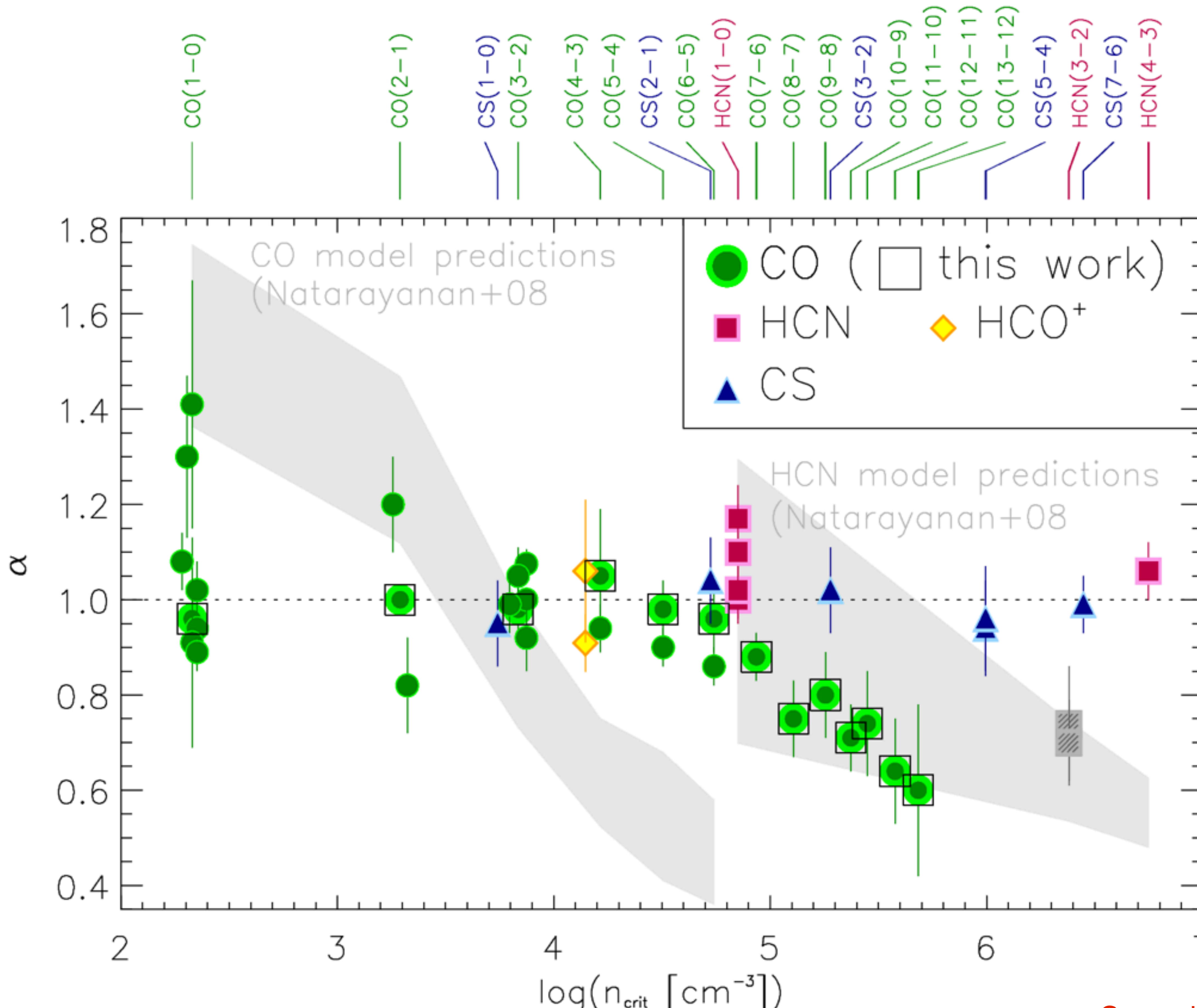

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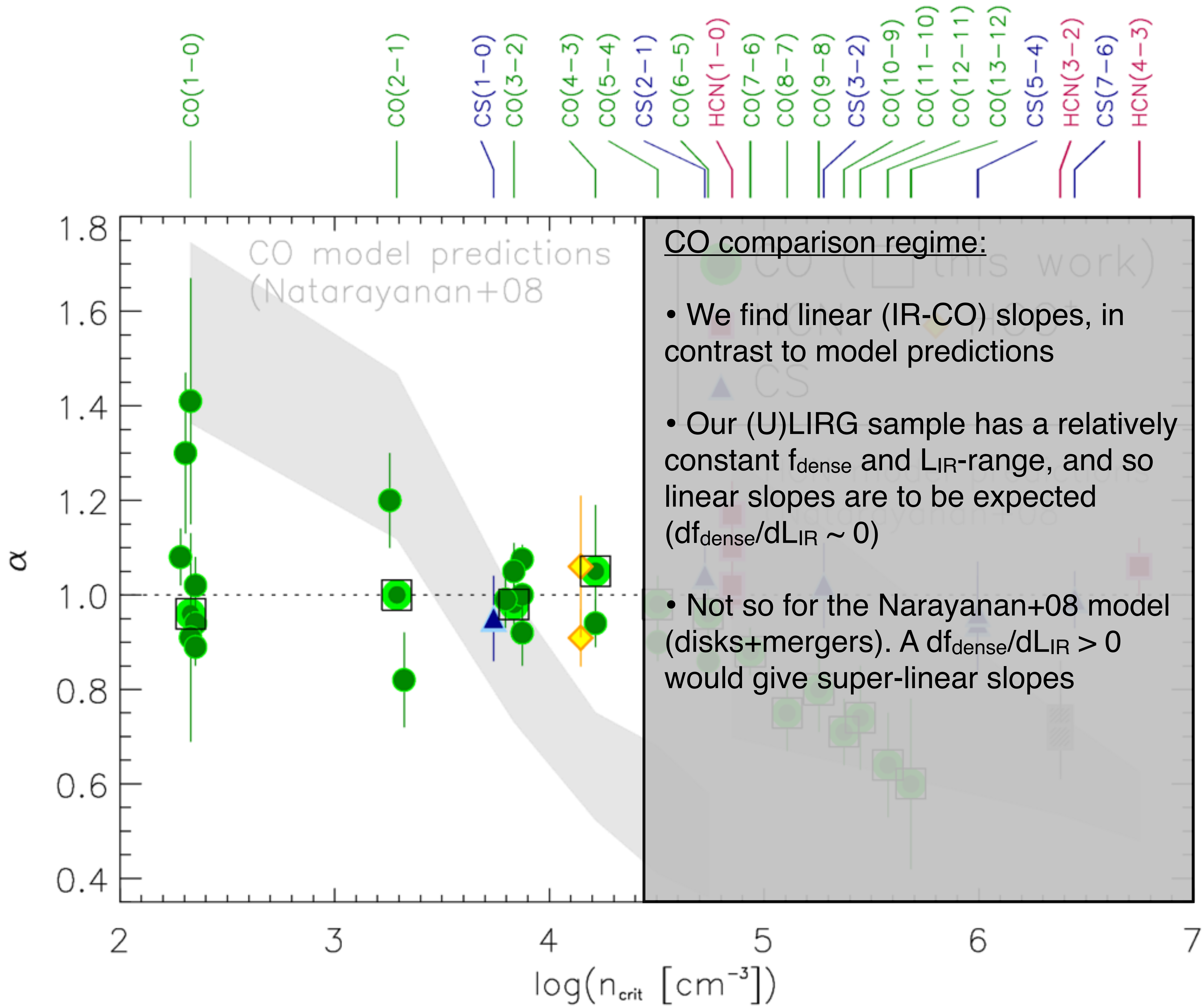
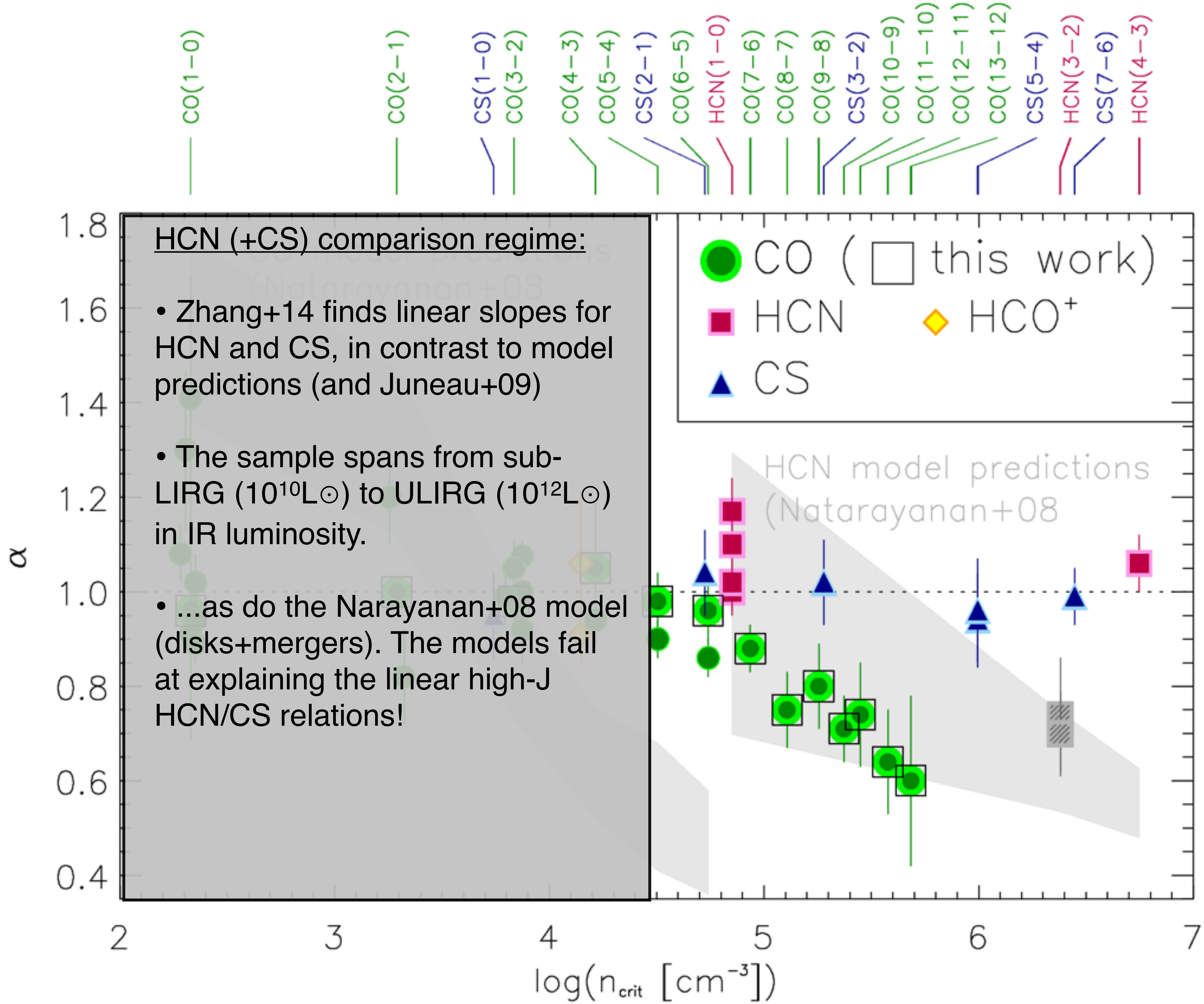


CO comparison regime:

- We find linear (IR-CO) slopes, in contrast to model predictions
- Our (U)LIRG sample has a relatively constant f_{dense} and L_{IR}-range, and so linear slopes are to be expected ($df_{dense}/dL_{IR} \sim 0$)
- Not so for the Narayanan+08 model (disks+mergers). A $df_{dense}/dL_{IR} > 0$ would give super-linear slopes

L_{IR}-L'_{mol} slope vs. n_{crit}(mol)



HCN (+CS) comparison regime:

- Zhang+14 finds linear slopes for HCN and CS, in contrast to model predictions (and Juneau+09)
- The sample spans from sub-LIRG (10^{10}L⊙) to ULIRG (10^{12}L⊙) in IR luminosity.
- ...as do the Narayanan+08 model (disks+mergers). The models fail at explaining the linear high-J HCN/CS relations!

Radiation pressure and the Eddington limit

• The maximal $(L_{IR}/M_{dense})_{Edd} \sim 500 L_\odot/M_\odot$ set by radiation pressure (Scoville & Polletta 2001)

• IR-CO relation can be derived in the case of Eddington limited ('maximal') star formation (Andrews & Thompson 2011)

$$L_{\rm Edd} = \underbrace{4\pi G c \kappa^{-1} X_{\rm CO}}_{\text{normalisation } (\beta)} L'_{\rm CO}$$

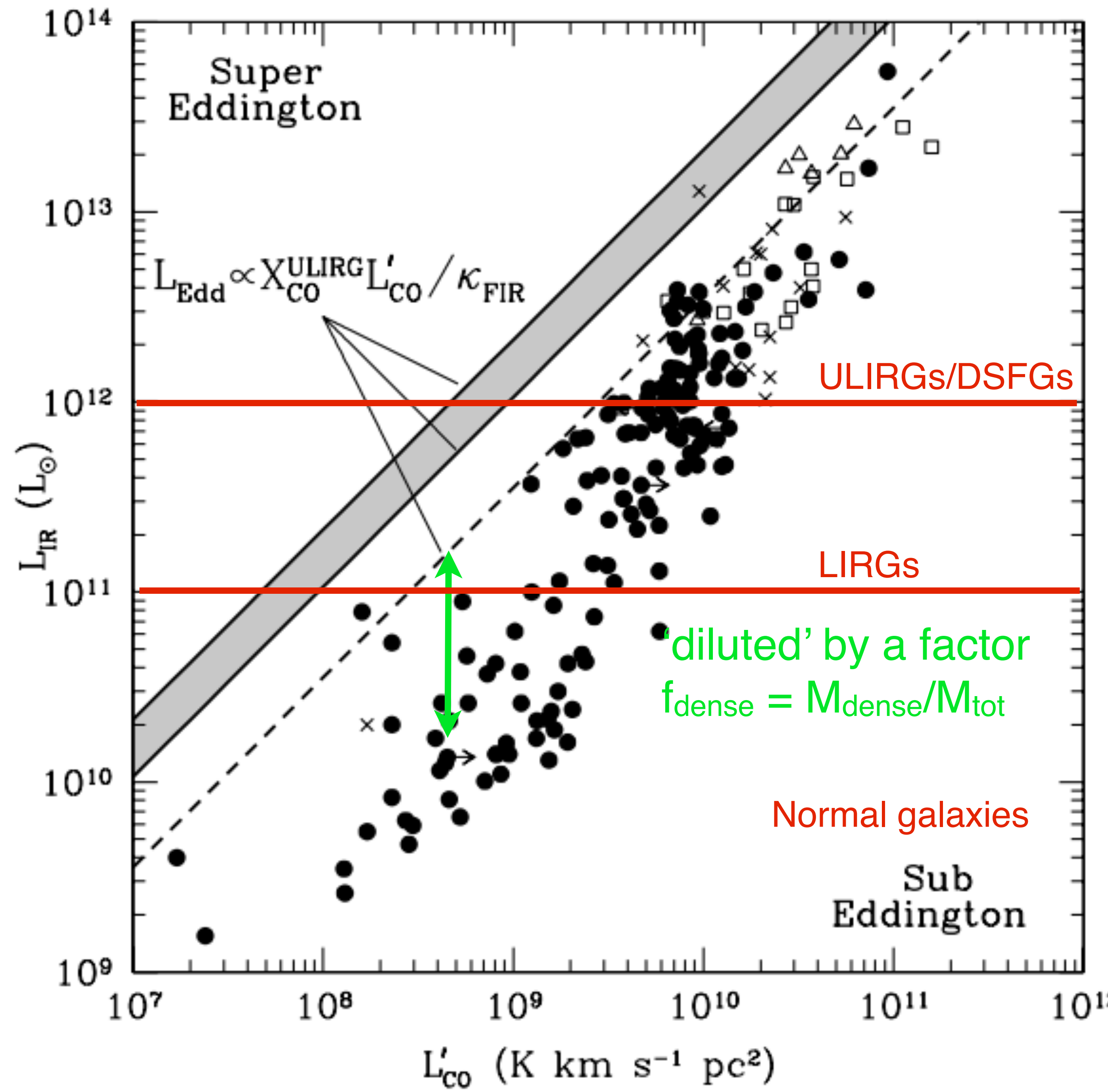
• Local (U)LIRGs and high-z DSFGs are highly dust-obscured and have nearly $(SFR)_{Edd}$ *on a global scale*

• In normal galaxies $(SFR)_{Edd}$ occurs deep inside individual clouds, but on a global scale the SFR is diluted by f_{dense}

• Super-linear slopes come about from varying $f_{dense}(L_{IR})$, or rather varying $\beta(L_{IR})$

→ **Bringing back bi-modal (global) CO SF laws!**

Note the correlations are linear!



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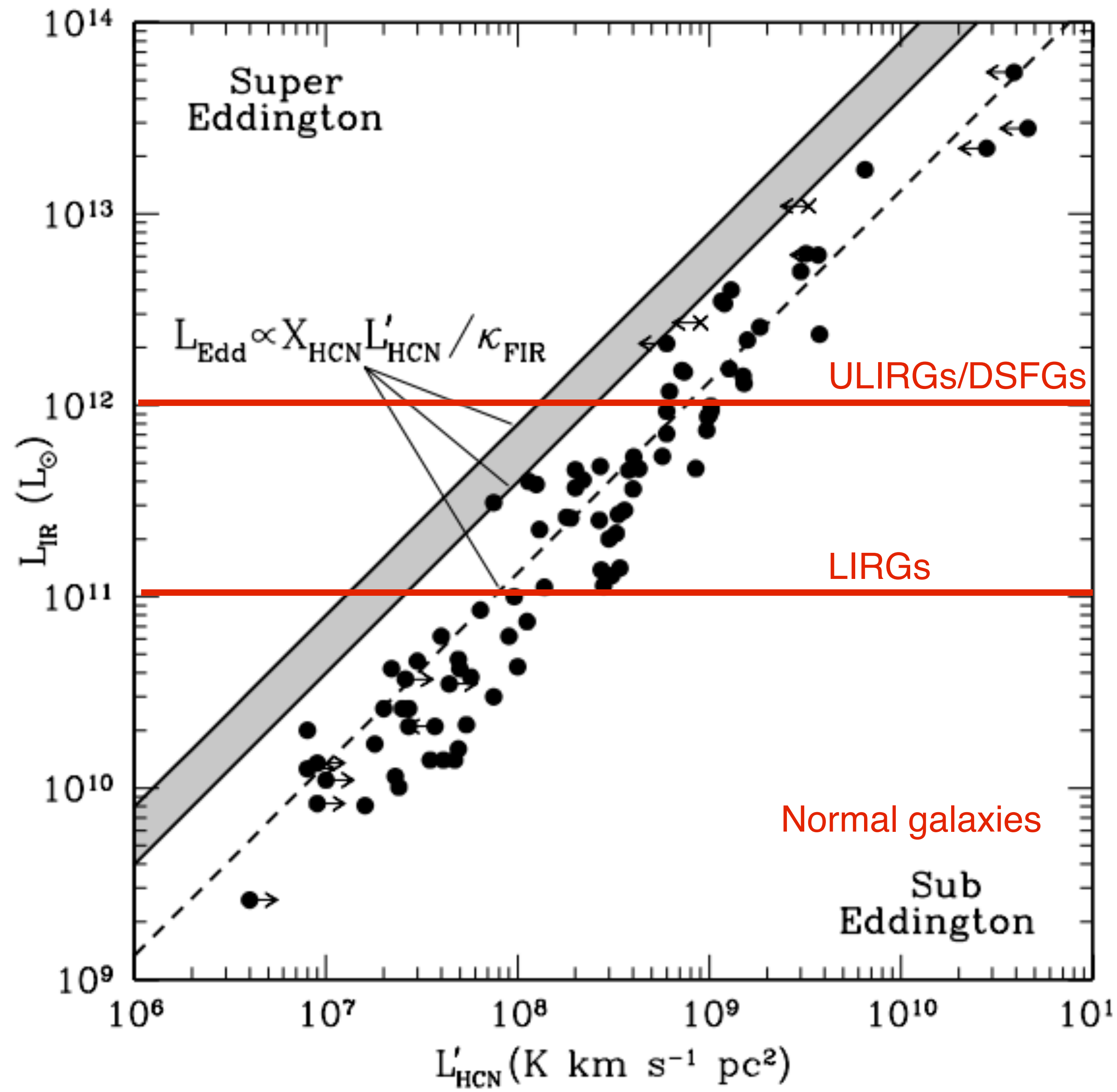
$$L_{\rm Edd} = \underbrace{4\pi G c \kappa^{-1} X_{\rm HCN}}_{\text{normalisation } (\beta)} L'_{\rm HCN}$$

• The density regimes probed by HCN (and CS) are $(SFR)_{Edd}$ regions, regardless of which galaxy the region resided in.

→ **A universal, linear dense SF law**

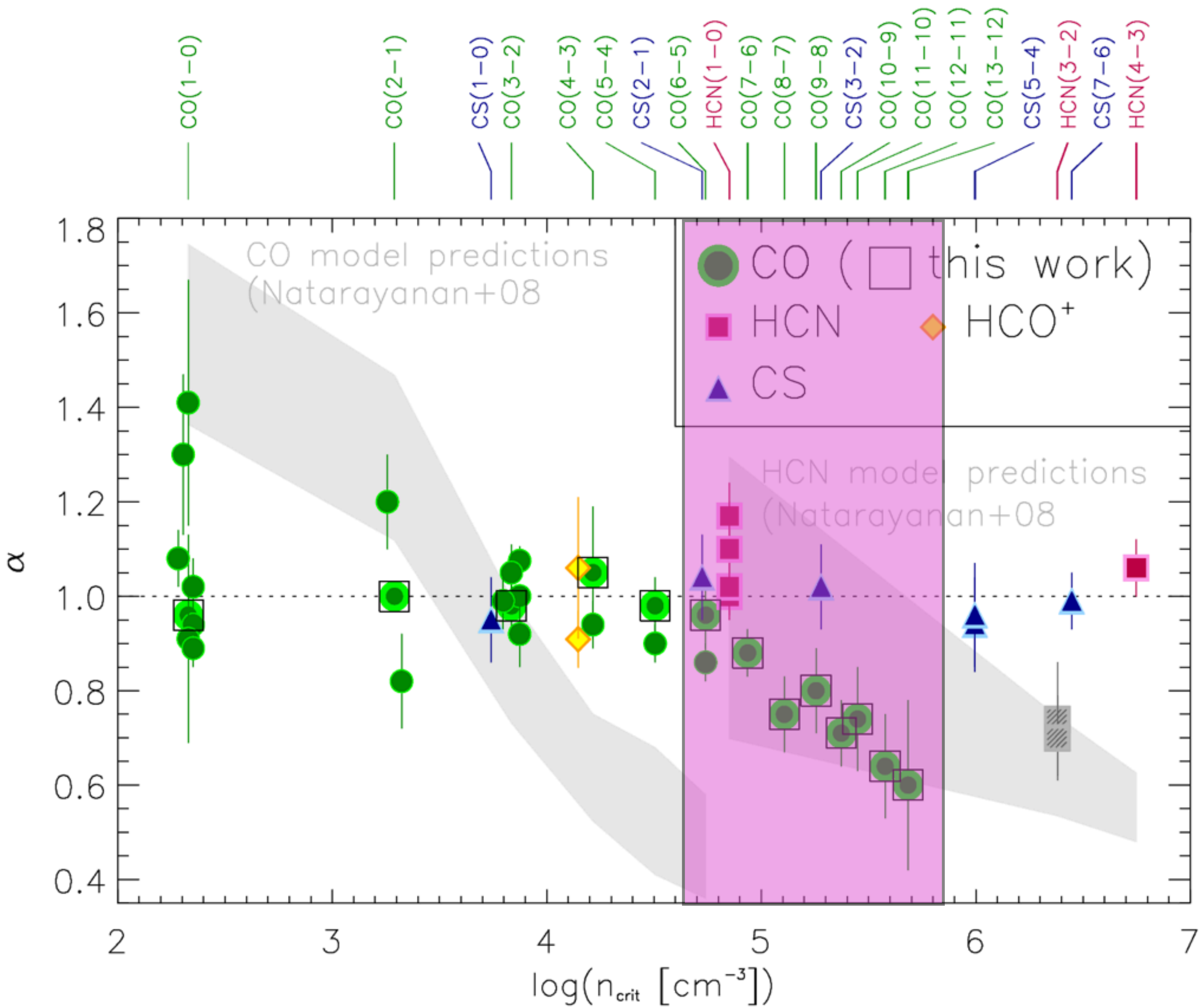
- Employs self-gravity **and** feedback
- Explains low-J CO and dense gas slopes
- Dense tracers are counting SF 'units'

Note the correlation is linear!



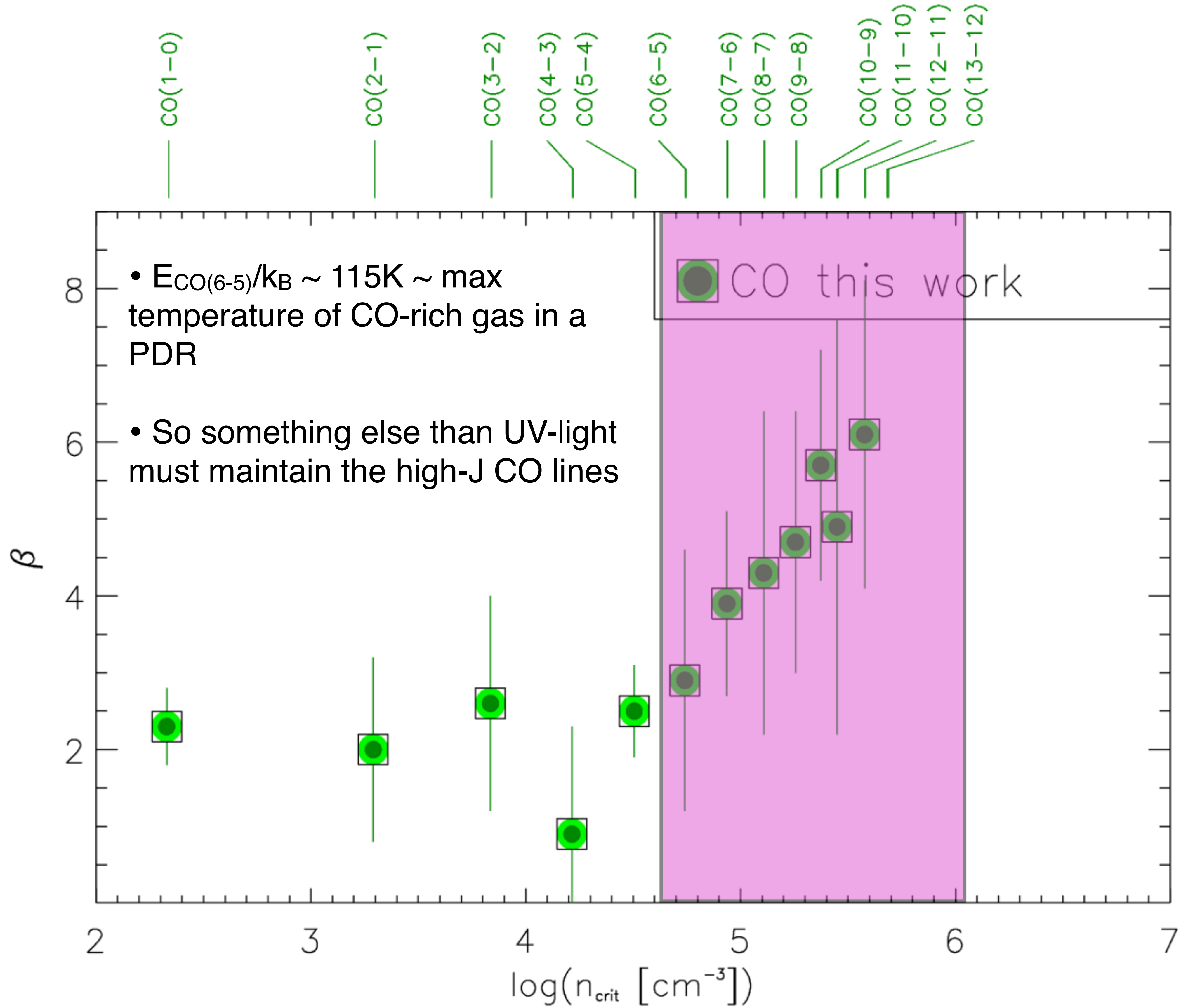
Andrews & Thompson (2011)

What about the high-J CO lines?



What about the high-J CO lines?

- $E_{CO(6\text{-}5)}/k_B$ ~ 115K ~ max temperature of CO-rich gas in a PDR
- So something else than UV-light must maintain the high-J CO lines



What about the high-J CO lines?

The decrease in α and increase in β at high-J can be explained by a simple argument:

$$\alpha_{\mathrm{CO_{J,J-1}}} = \frac{d\log L_{\mathrm{IR}}}{d\log L'_{\mathrm{HCN_{1,0}}}} \times \frac{d\log L'_{\mathrm{HCN_{1,0}}}}{d\log L'_{\mathrm{CO_{1,0}}}}$$

$$= \alpha_{\mathrm{HCN_{1,0}}} \left(1 + \frac{d\log l_{\mathrm{dense_{J,J-1}}}}{d\log L'_{\mathrm{CO_{J,J-1}}}}\right)$$

$$l_{\mathrm{dense_{J,J-1}}} = L'_{\mathrm{HCN_{1,0}}}/L'_{\mathrm{CO_{J,J-1}}}$$

determines deviations in $\alpha_{\mathrm{COJ,J-1}}$ from unity and depends on both the dense gas fraction and the global excitation

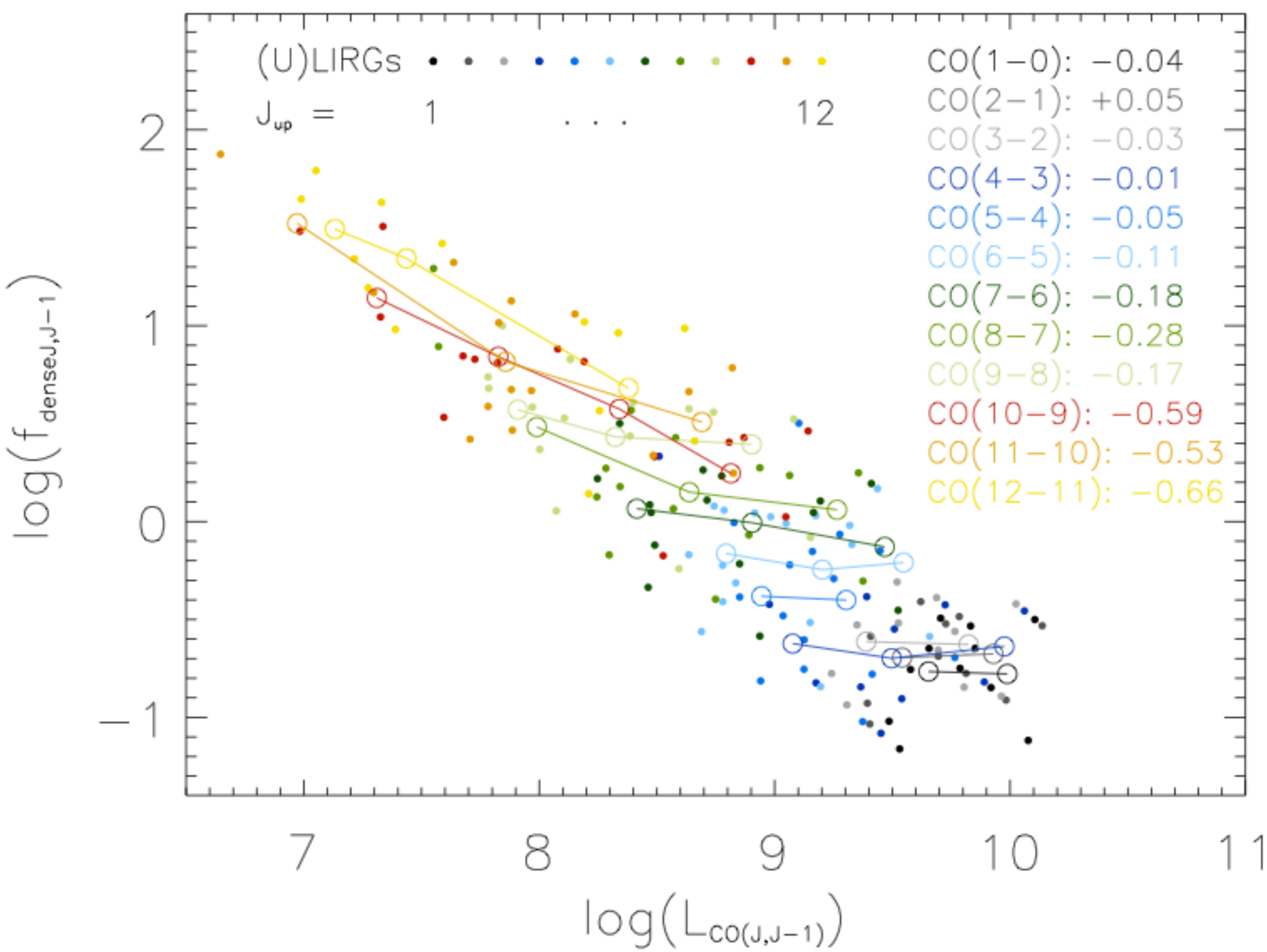
<u>Low-J:</u> l_{dense} ~ dense gas fraction ~ constant for a ‘homogeneous’ sample and so α ~ 1

<u>High-J:</u> $l_{\mathrm{dense}} \sim R_{\mathrm{d,d\text{-}w}} = M_{\mathrm{dense}}/M_{\mathrm{dense\text{-}warm}} > 1$

Evidence of a new warm, dense gas phase in (U)LIRGs

• Evidence for an increasing mass and/or excitation of the warm and dense (d-w) gas phase relative to the dense gas reservoir (d)

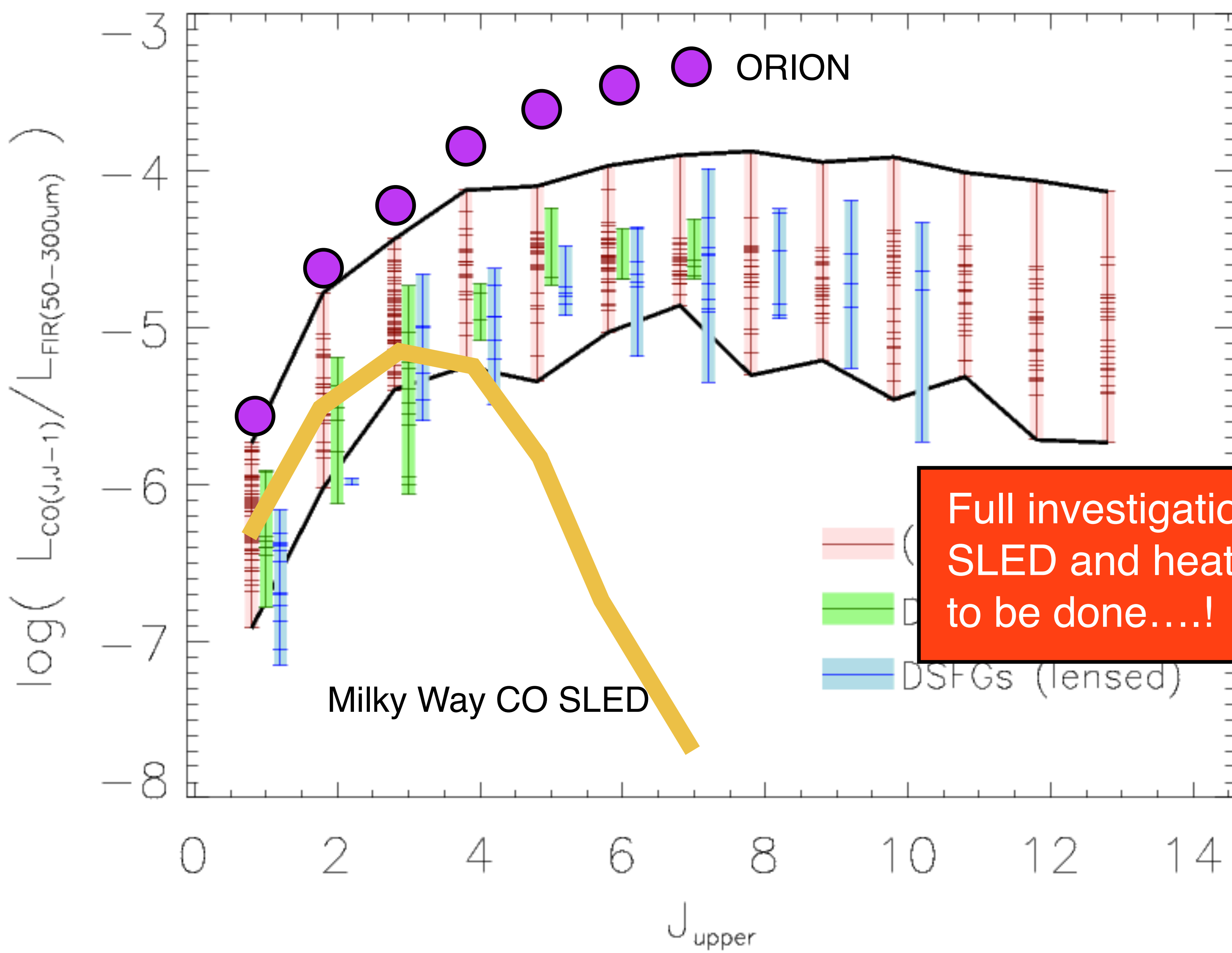
• Indicates the presence of a significant warm (T_k >100K > T_{dust}) and dense (>$10^4 cm^{-3}$) gas component that is not tied to the star formation via UV/optical heating. Suggestive of alternative heating mechanisms (cosmic rays, turbulence/shocks)



Evidence of a new warm, dense gas phase in (U)LIRGs

- A generic characteristic of low- and high-z merger/starbursts:
  - *global* CO SLEDs remain nearly flat out to J=13-12!
  - Radically different from MW/quiescent CO SLEDs

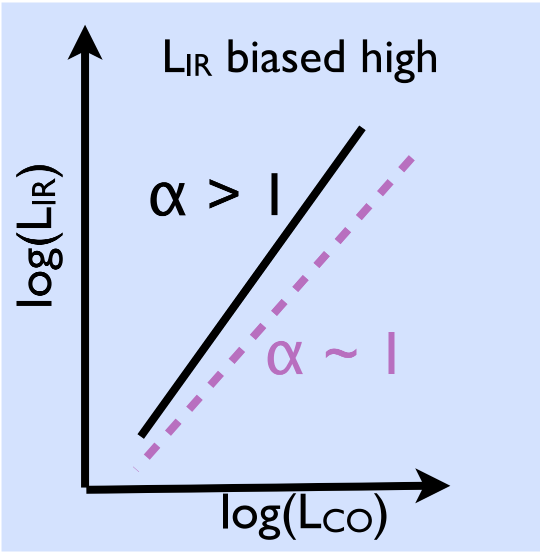
- This is impossible to maintain on a *global* scale simply by UV-photons

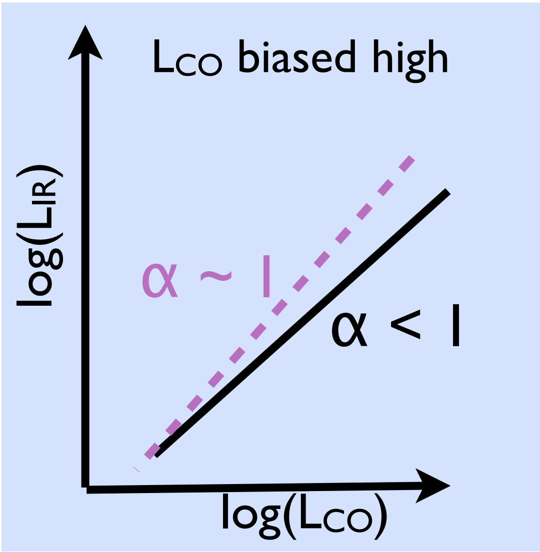


Full investigation of high-J CO SLED and heating mechanisms to be done….!

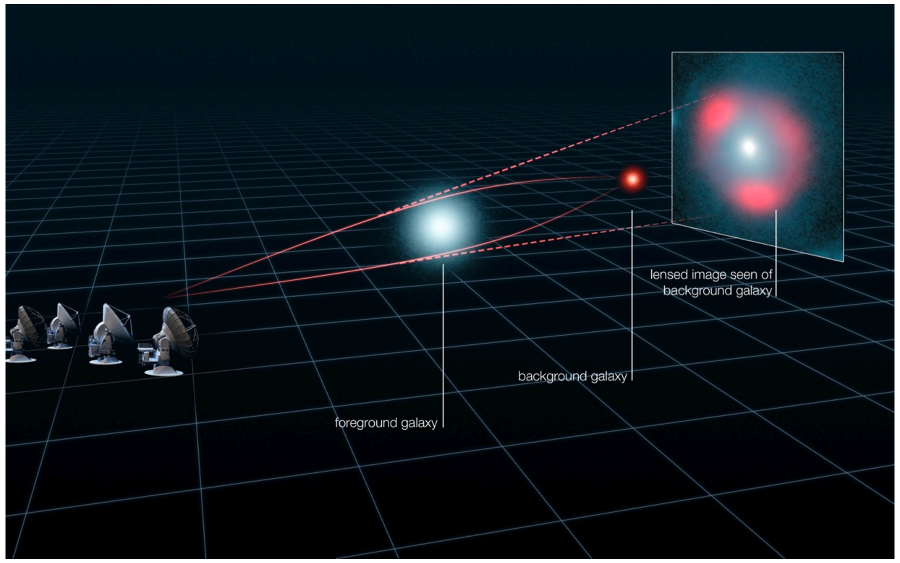
Caveats and possible biases

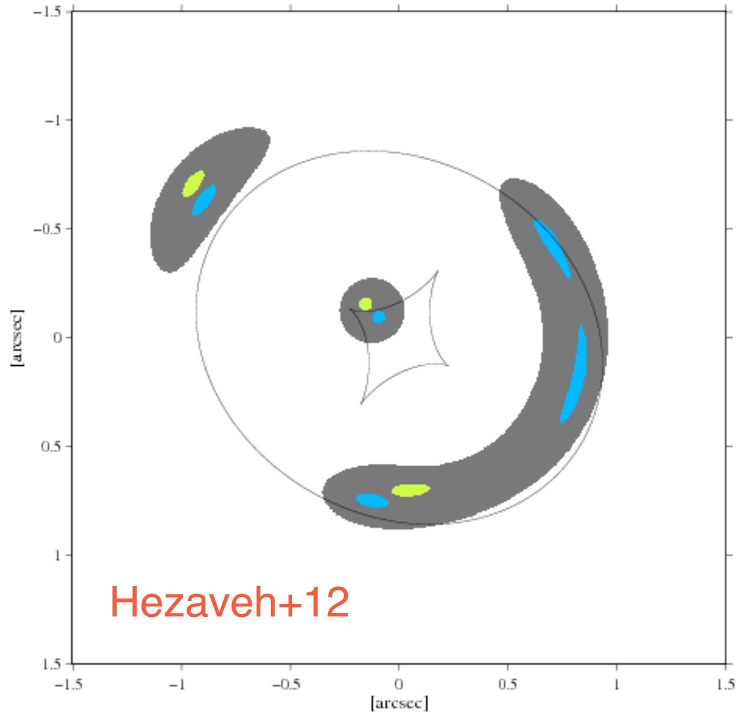
- AGN contamination
    - high IR luminosities (bias α high)
    - XDRs 'boosted' high-J lines (bias α low)
    - Removed AGN

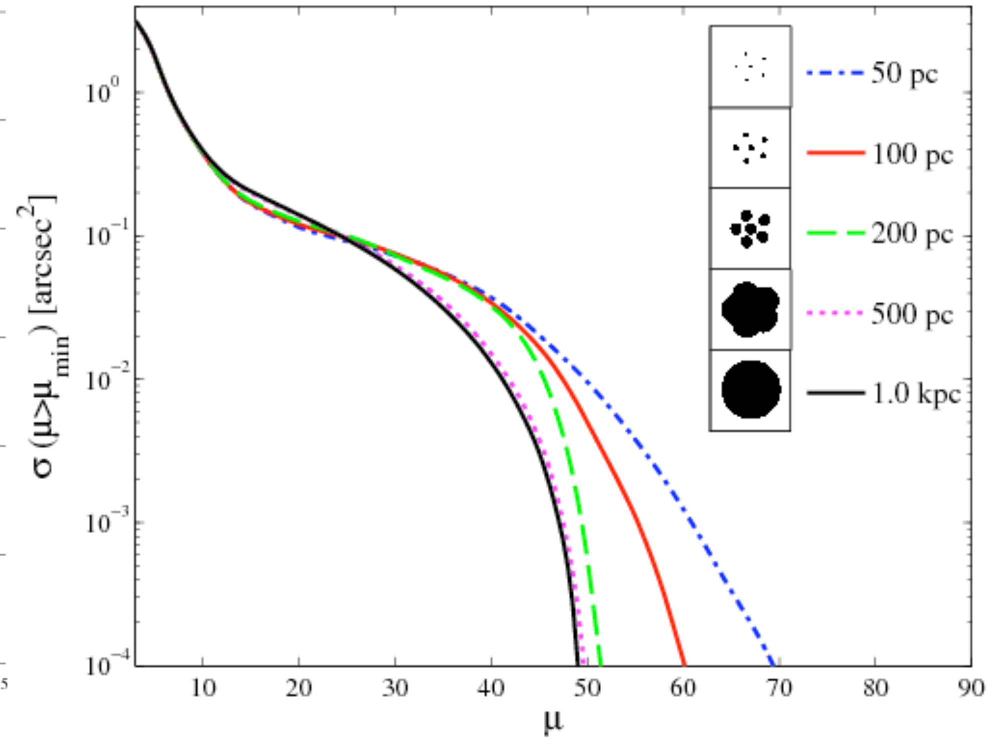




- Differential lensing (Blain+98; Hezaveh+12; Serjeant+12)
    - high IR luminosities (bias α high)
    - XDRs 'boosted' high-J lines (bias α low)
    - But correlations unchanged if we discard lensed DSFGs



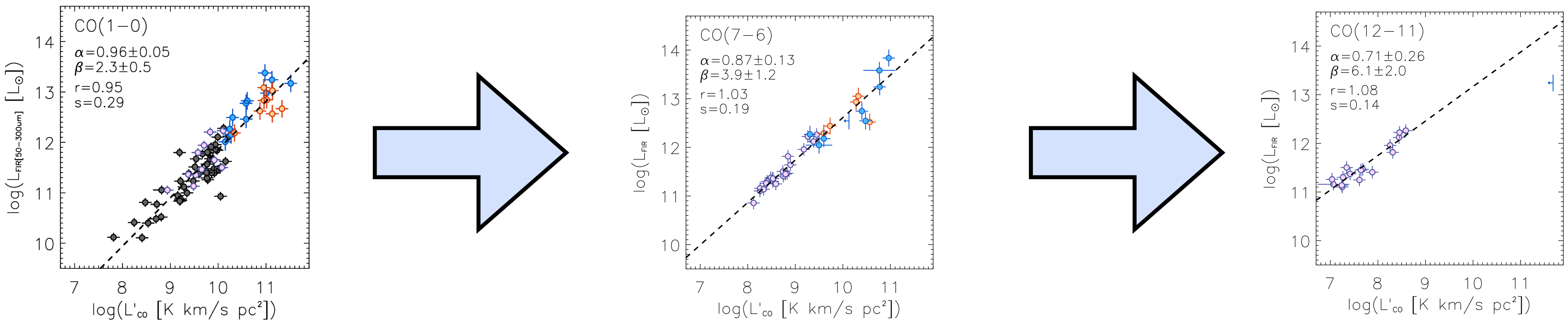




- Small dynamical range in luminosities for high-J lines

Conclusions & Future Work

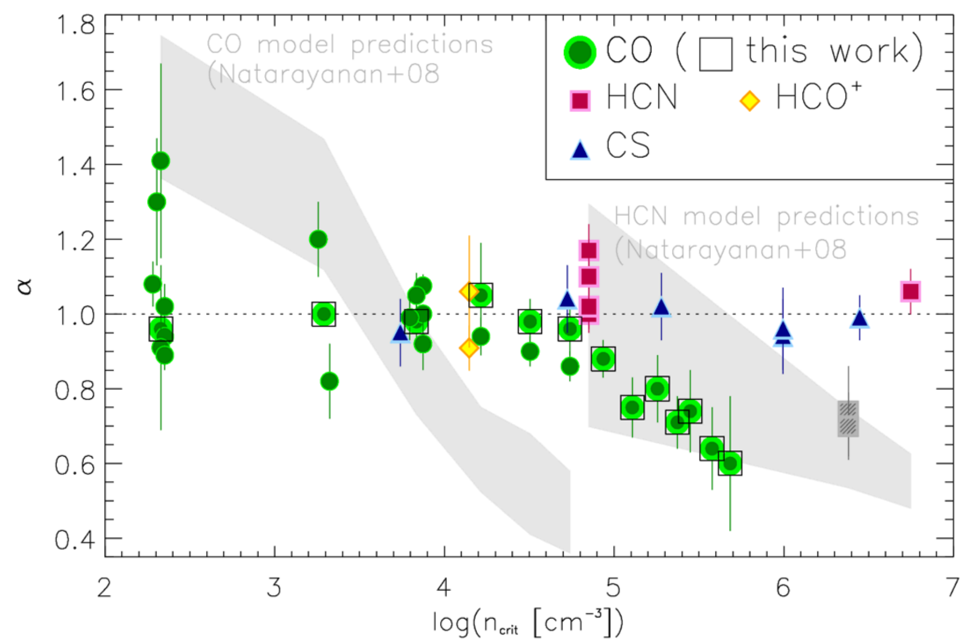
- Delineated L_{IR}-L_{CO} relations across the full CO J-ladder for a statistically significant sample of (U)LIRGs

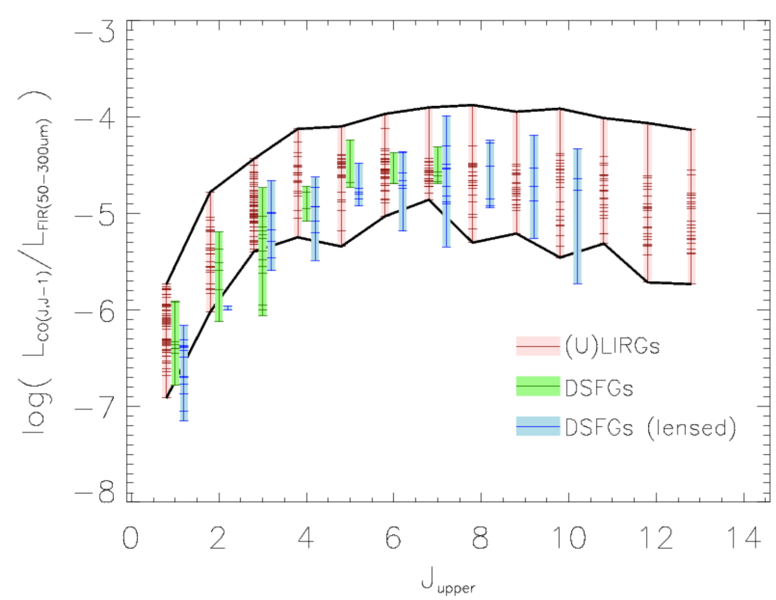


OPEN QUESTIONS:

•What powers the high-J molecular lines in the ISM of (U)LIRGs, high-z DSFGs?

- **CRs, turbulence, shocks?**
- **Related issues: SF initial conditions (IMF), turbulence dissipation, etc**



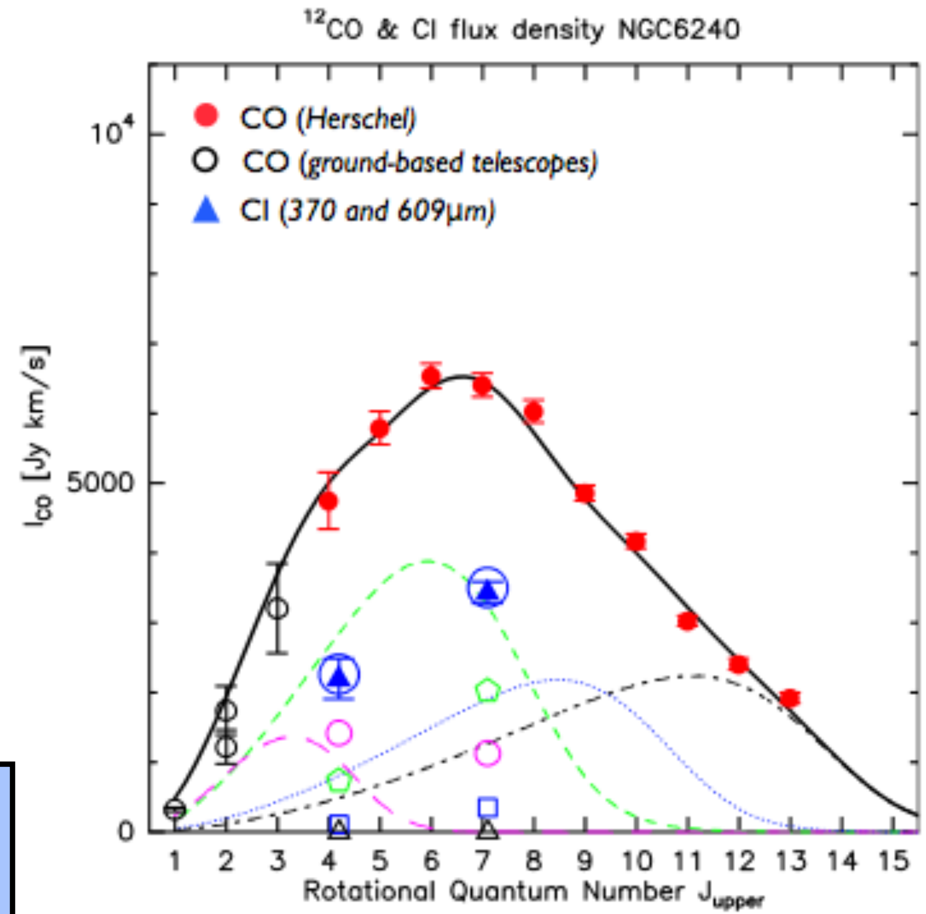


- 'Flat' global CO SLEDs out to J=13-12
  - Presence of a significant (in terms of mass) warm, dense phase
  - Likely heating mechanisms are CRs and shocks (UV-photons unlikely)

Conclusions & Future Work

- Full multi-line, multi-phase LVG modeling of the ISM

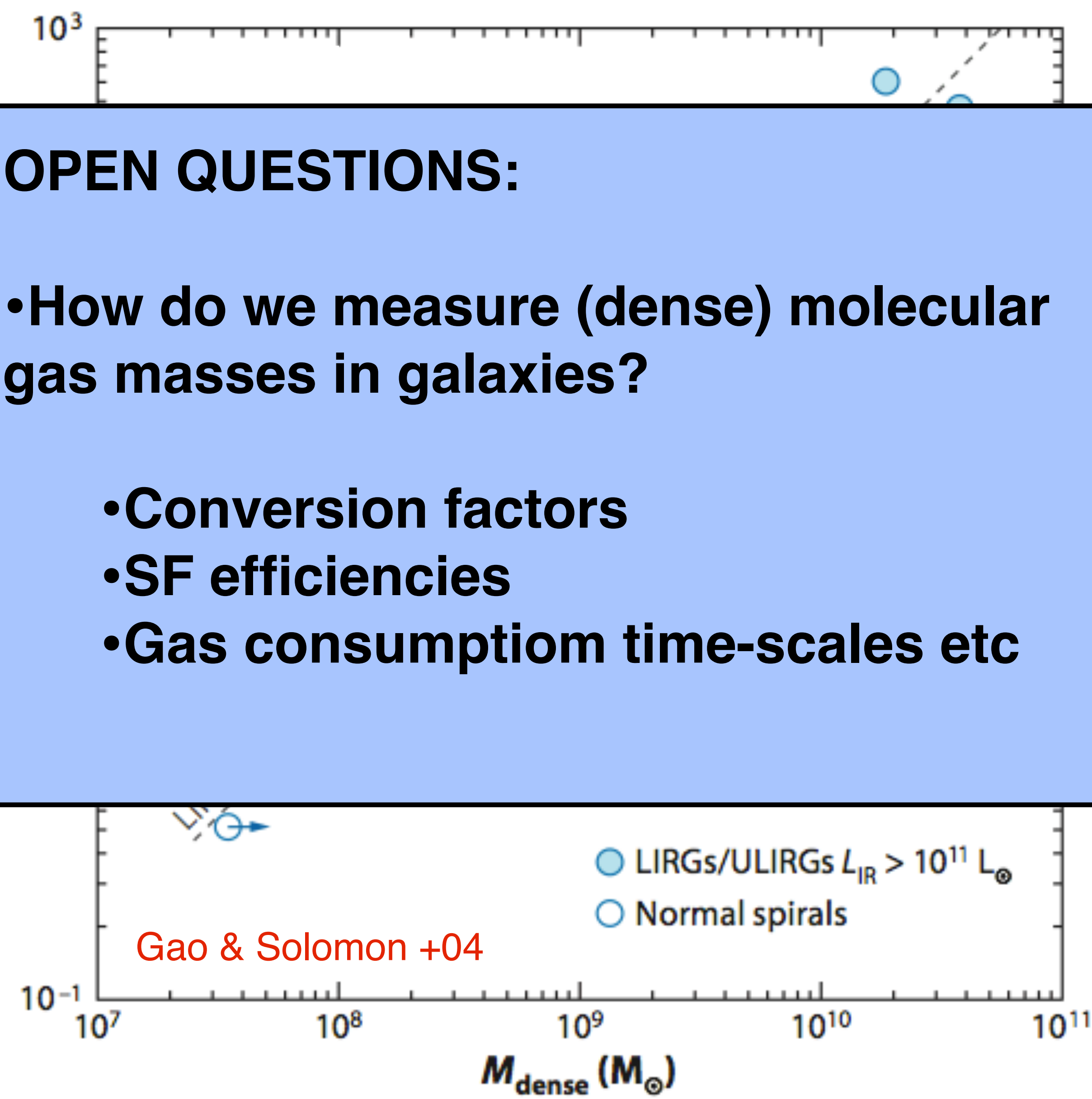
- Explore SFR - M_{dense} relations instead of luminosity relations (work in progress) based on *accurate source-by-source M_{dense} estimates!*

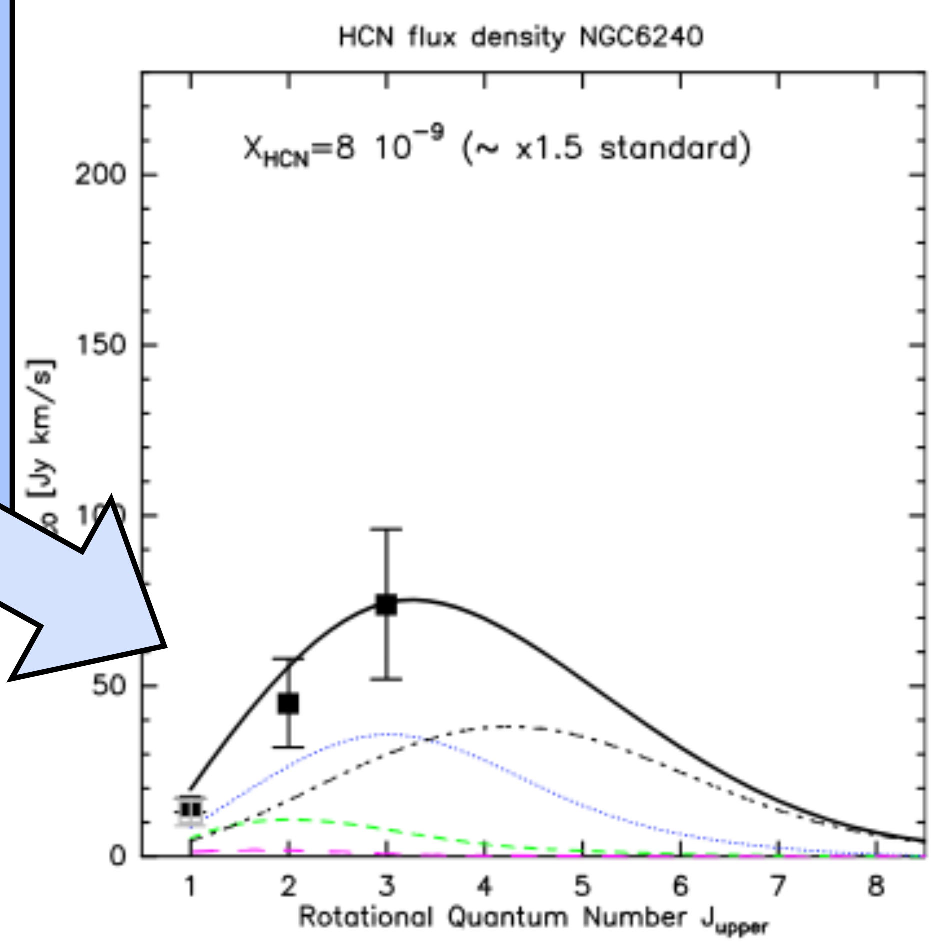


OPEN QUESTIONS:

•How do we measure (dense) molecular gas masses in galaxies?

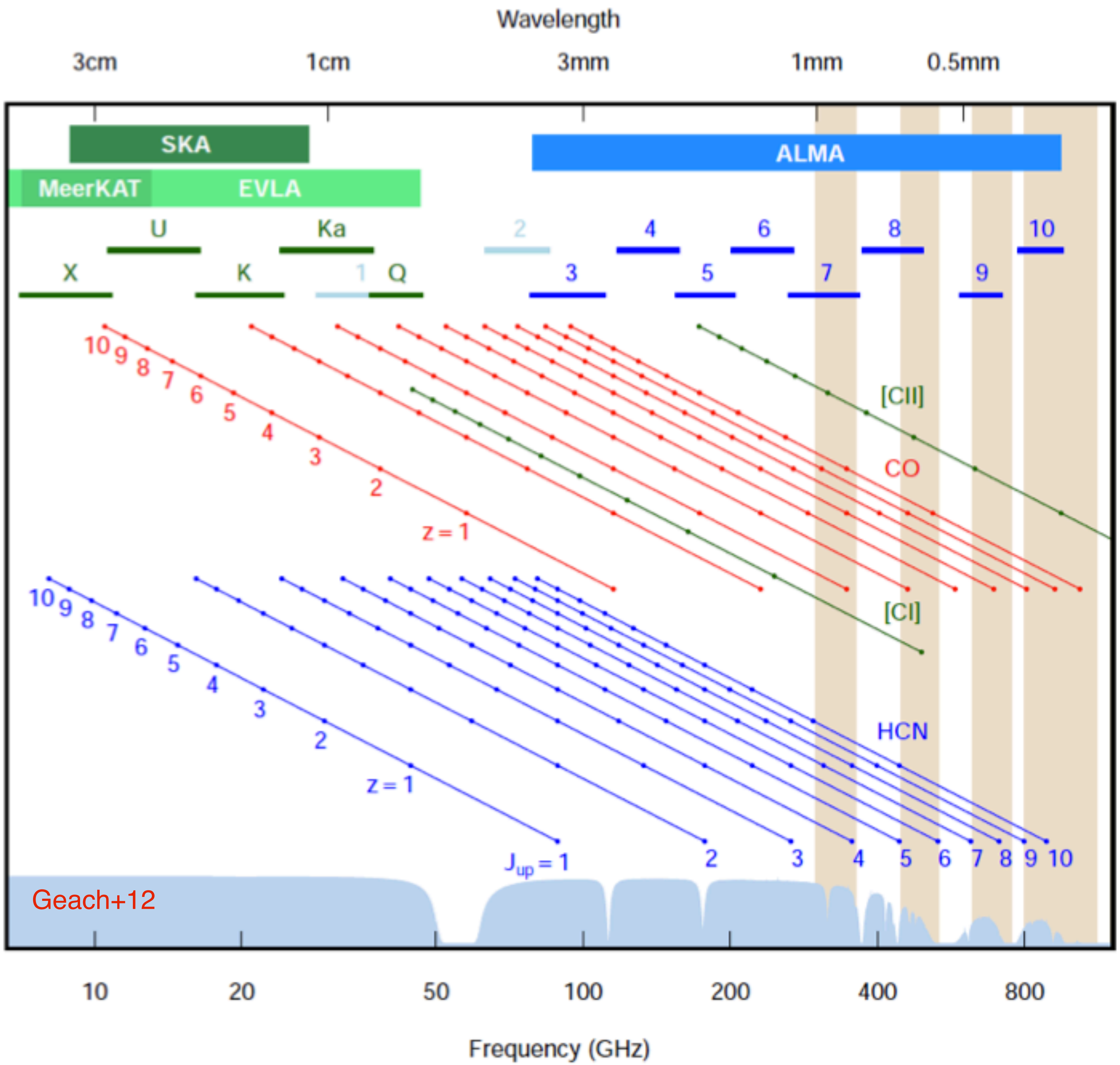
- **Conversion factors**
- **SF efficiencies**
- **Gas consumptiom time-scales etc**





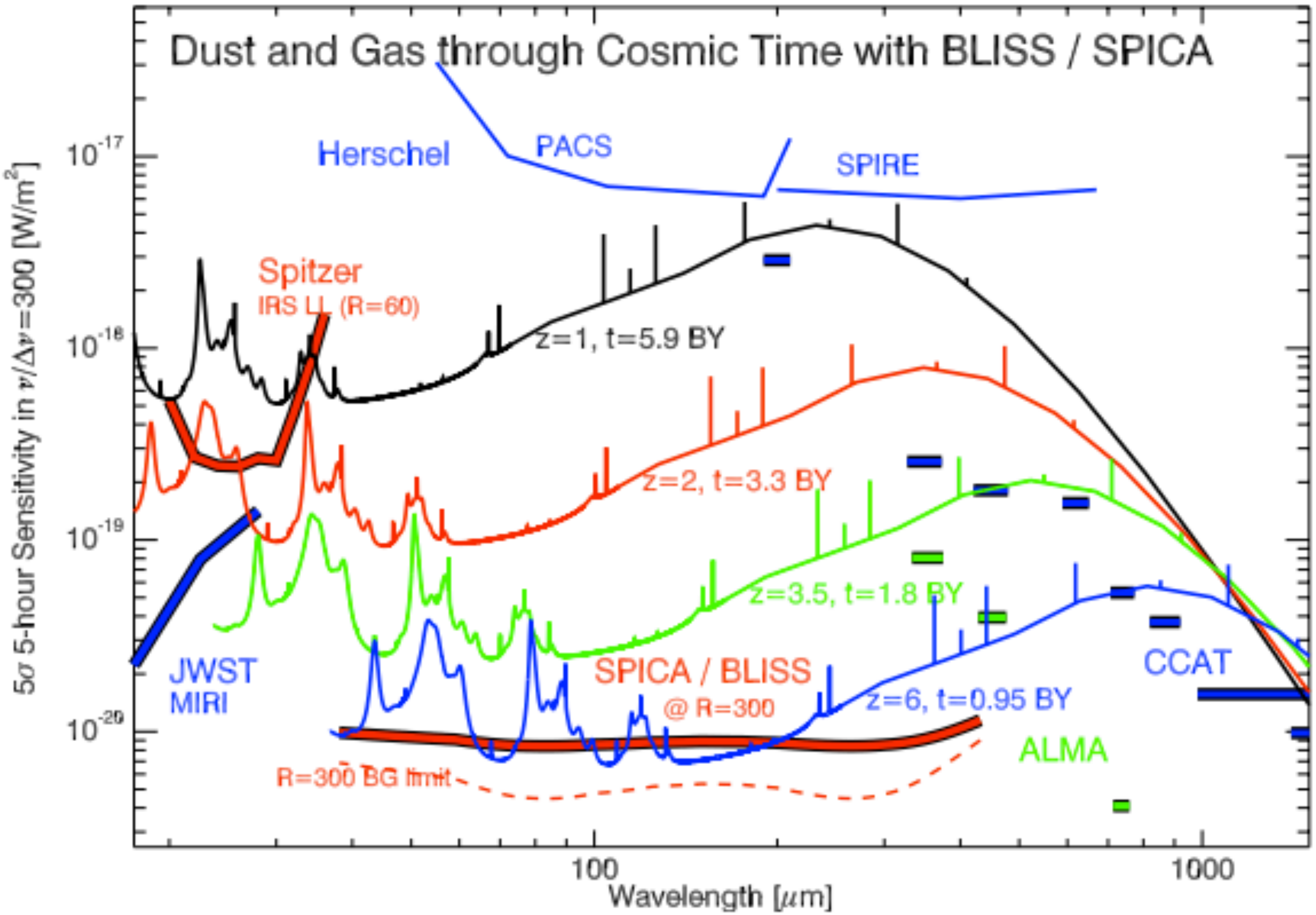
Conclusions & Future Work

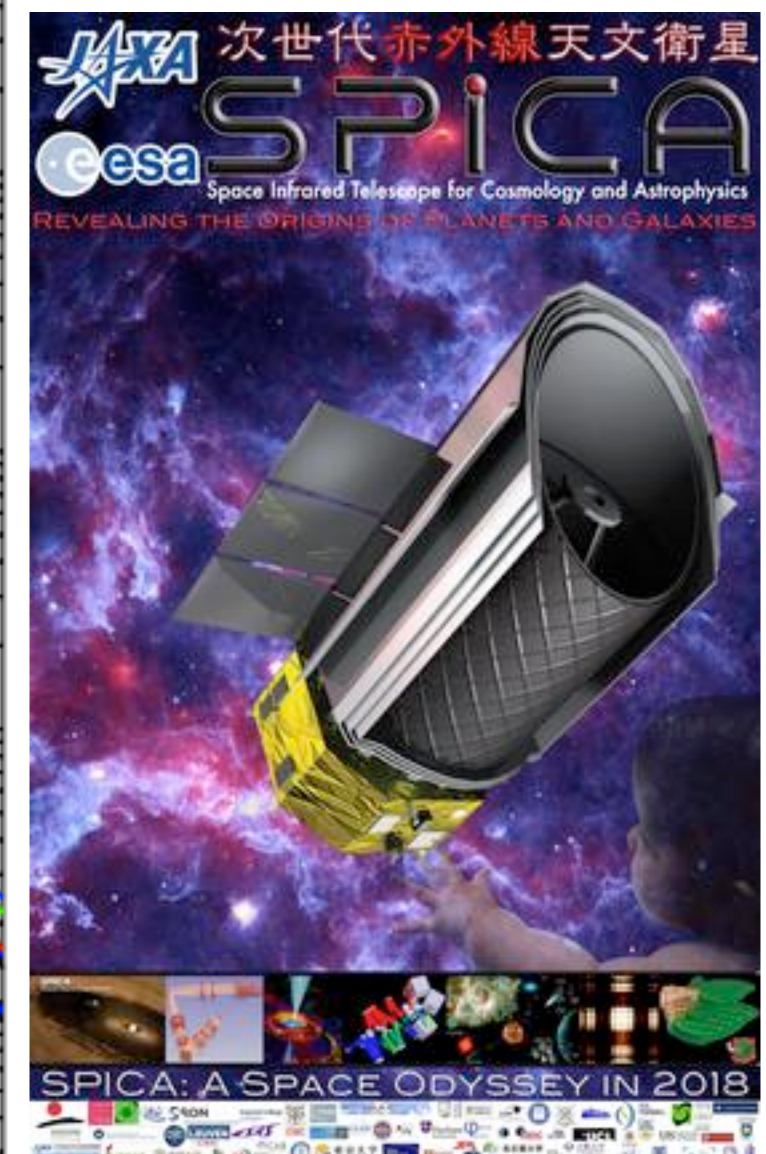
- Spatially resolved high-J CO, HCN, CS observations with ALMA. Resolved dense gas SF relations.



Conclusions & Future Work

- For the highest-J lines, (>1THz), single-dish telescopes will remain important
- Herschel Science Archive (large part still unexplored), and **SPICA, CCAT**

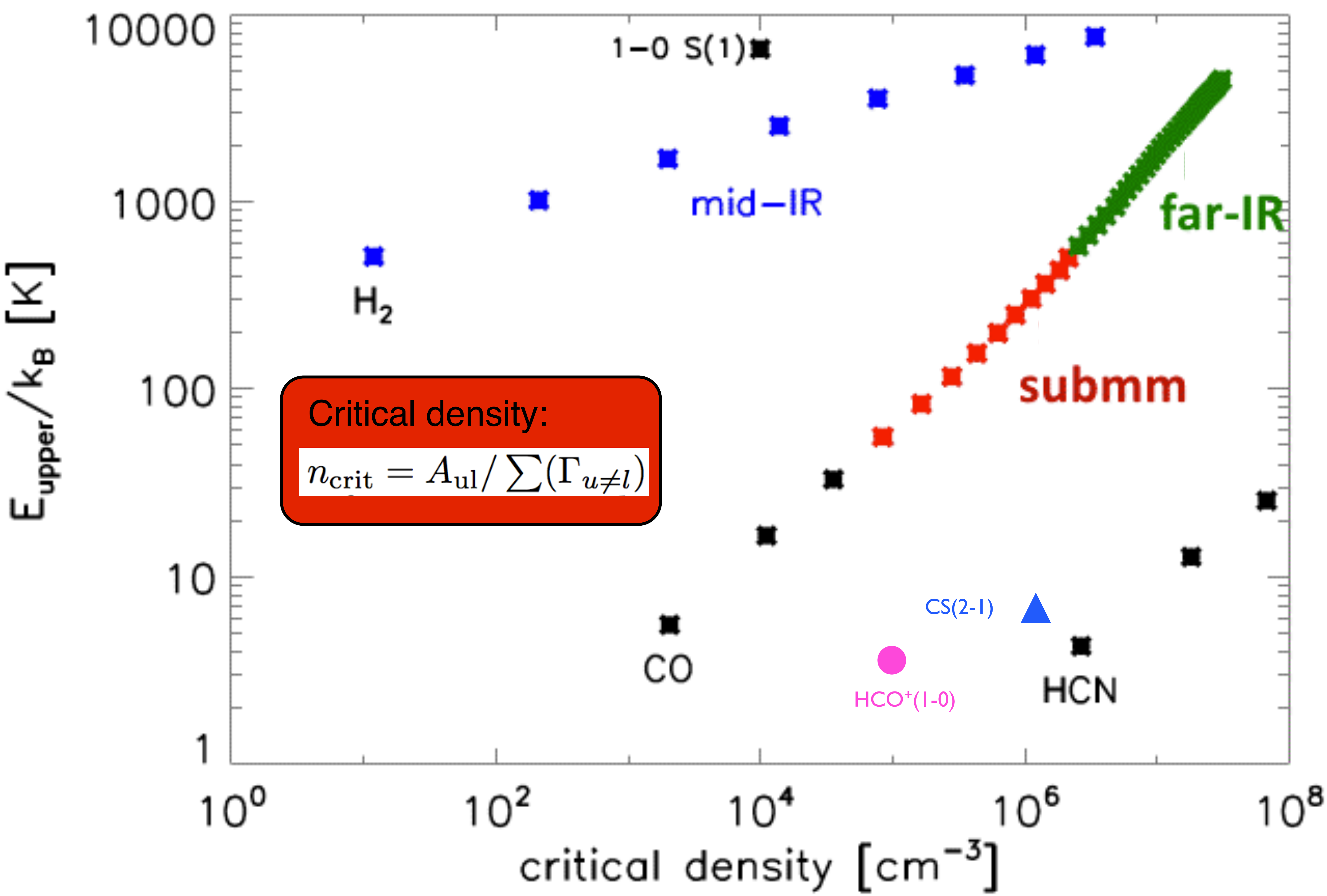




The End

Thanks for listening,
...and sorry for missing the plane!

Star formation relations in the high density regime



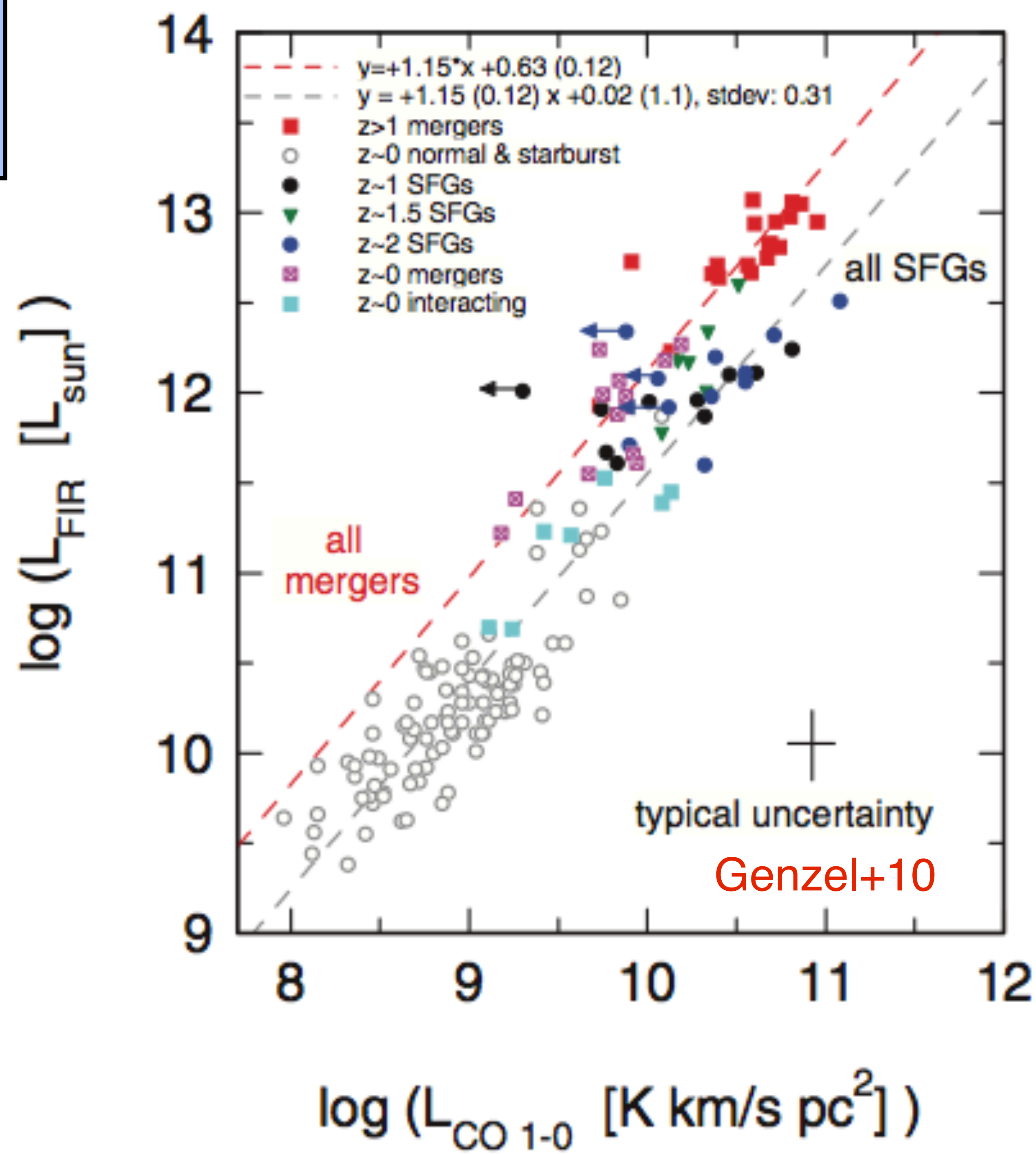
Luminosity (IR-CO) relations at high redshifts

Slope determinations:

- **Greve+05 (12 SMGs + LIRGs): $\alpha = 1.5 \pm 0.3$**
- **Iono+09 (SMGs+LIRGs, CO(3-2) only): $\alpha = 1.10 \pm 0.03$**
- **Genzel+10 (10 SMGs + LIRGs): $\alpha = 1.15 \pm 0.12$**
- **Bothwell+13 (>30 SMGs + LIRGs): $\alpha = 1.20 \pm 0.13$**
- **Ivison+11 (SMGs+LIRGs, CO(1-0) only): $\alpha = 0.89 \pm 0.04$**

Bi-modal SF laws?

- Starburst mergers vs. quiescent disks
- Enhanced SFE in mergers
- Compact vs. extended gas configuration
- ISM energy density (UV, CR, turb.)

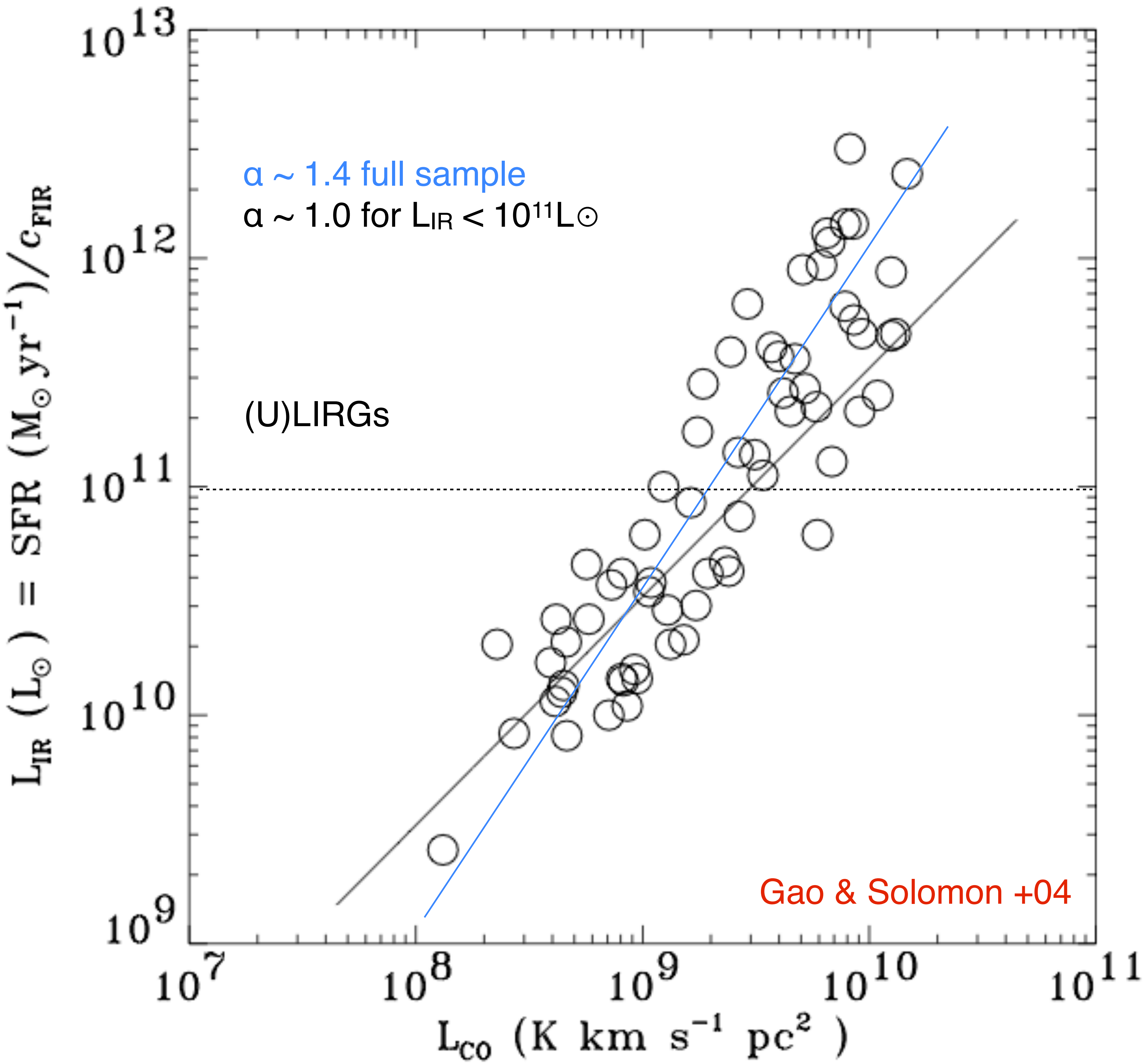


Issues:

- Heterogenous samples
- Poorly sampled SEDs / L_{IR} uncertain
- AGN contamination harder to assess
- Mixing J-transitions

Luminosity (IR-CO) relations of local galaxies

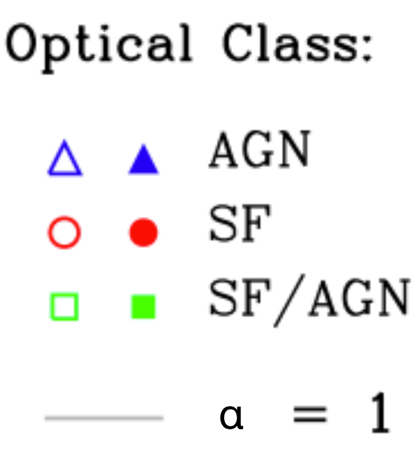
IR-CO(1-0)

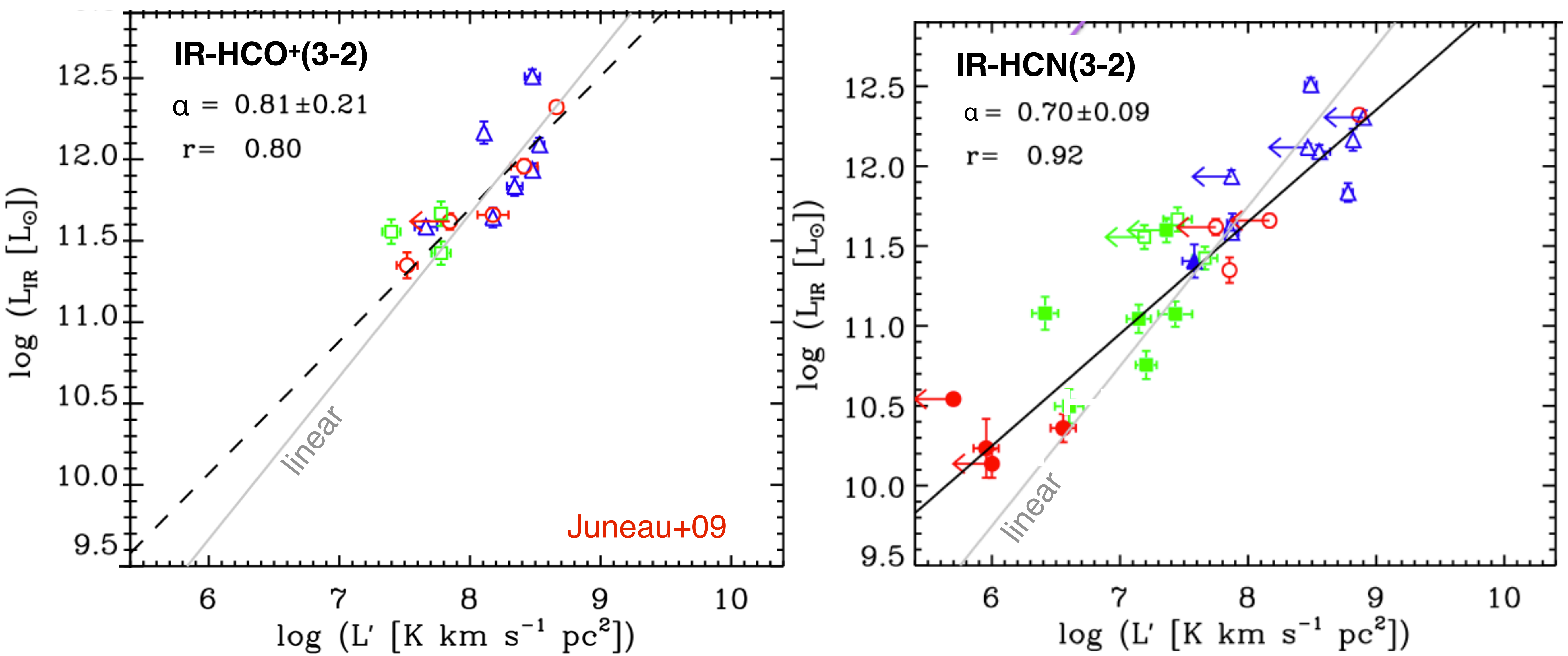


Luminosity (IR-dense gas) relations of local galaxies

IR-HCN/HCO+(3-2)

- Evidence for sub-linear slopes at high densities?
- We would expect linear relations at even higher n_{crit} than HCN(1-0)





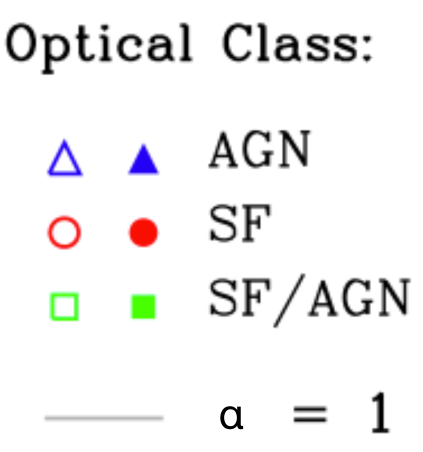
Luminosity (IR-dense gas) relations of local galaxies

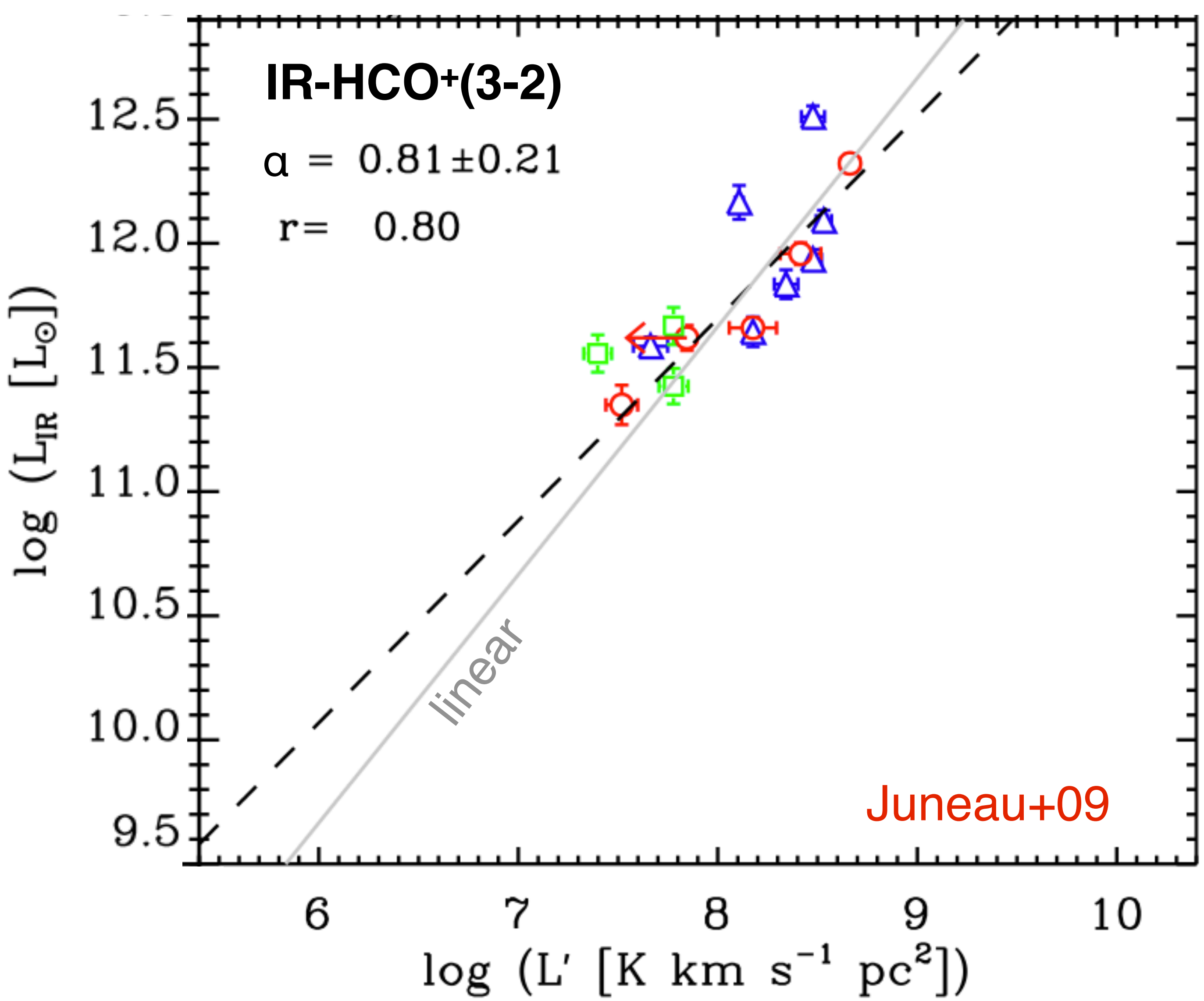
IR-HCN/HCO+(3-2)

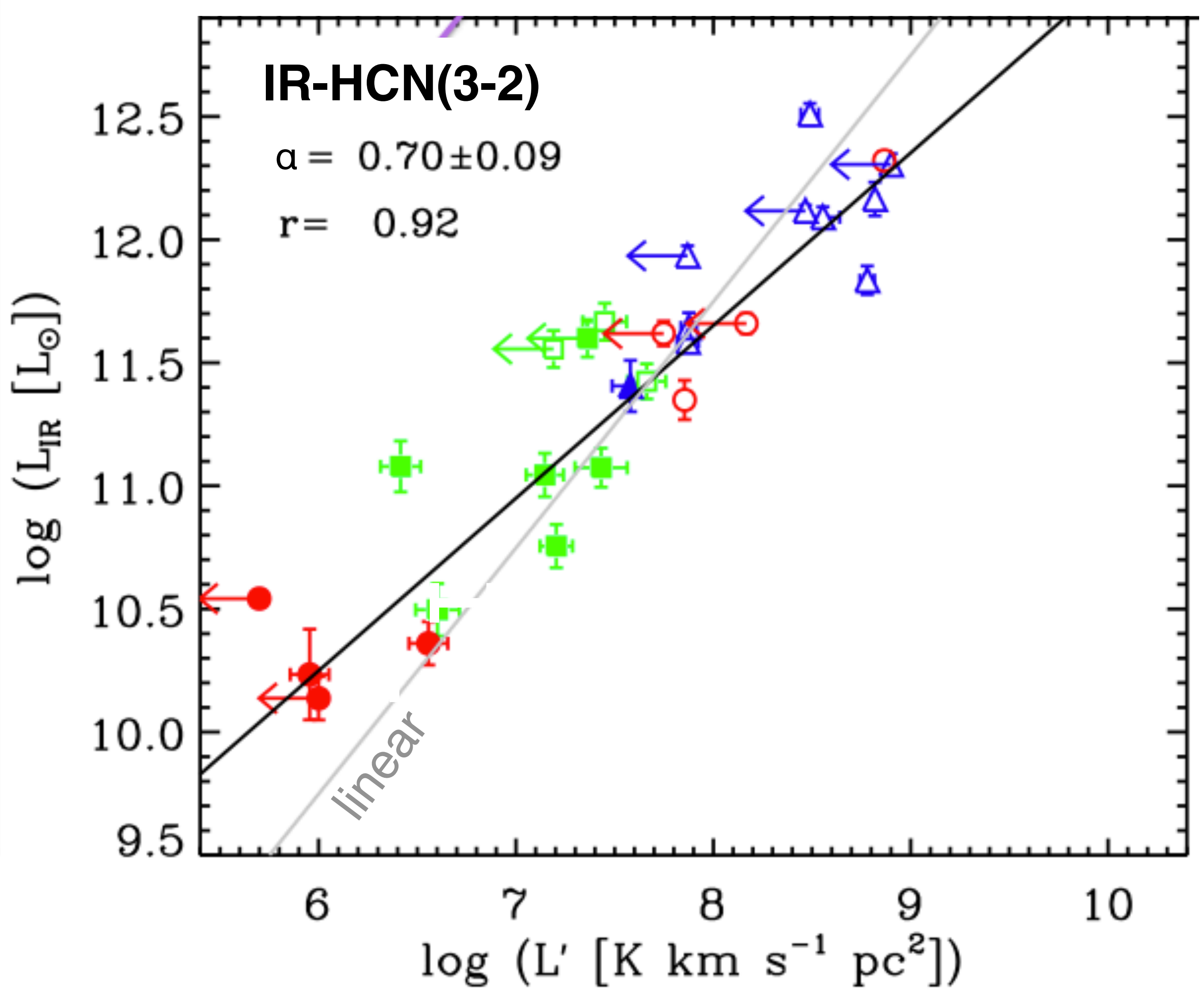
- Evidence for sub-linear slopes at high densities?

Issues:

- Small, heterogenous samples
- Not corrected for IR-mol beam matching
- HCO^+ ionic molecule, sensitive to e- abundance







Luminosity (IR-dense gas) relations of local galaxies

IR-HCN(1-0)

- (U)LIRGs have higher HCN/CO (i.e. dense gas fractions) than normal spirals.
- This explains the super-linear IR-CO relations ('mixing' populations)
- Bimodal IR-CO relations, with f_{dense} setting the IR-CO normalisation (β)